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QUARRY FILLING WITH CEMENT-STABILIZED FLY ASH

Report No 91-259-K

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ABSTRACT

The Lakeview Ash Management Study (LAMS) team is proposing the placement of 2 million m^3 fly ash in a mined-out limestone/dolostone quarry in southern Ontario. The use of cement-stabilized fly ash is being considered for this project, in order to minimize environmental impact. This report examines the environmental impact of fly ash versus cement-stabilized fly ash for quarry filling. An analysis of the cost of cement-stabilized fly ash versus the proposed conventional containment systems is also included.

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QUARRY FILLING WITH CEMENT-STABILIZED FLY ASH

1.0 INTRODUCTION

Three limestone/dolostone quarries have been identified by the Lakeview Ash Management Study (LAMS) team and their consultants, Golder Associates, as possible locations for the placement of 2 million m^3 of Lakeview fly ash, beginning in 1994. These sites include the Lincoln Quarry near Beamsville, the Uhtoff Quarry near Orillia, and the Cayuga Quarry near Cayuga. Details related to the investigation and selection of these sites may be found elsewhere/1,2,3,4,5/. One of the goals of LAMS is to determine the containment design which would minimize both environmental impact and disposal costs.

Initially, one containment design was proposed for each of the three quarries. Upon a request from the LAMS team, alternate containment designs were developed for the Lincoln quarry and Uhtoff quarry. In all, five containment designs have been proposed/5/. Of the five designs proposed, the Lincoln original and the Cayuga original, have been identified as having the lowest combined construction and operational costs/5/.

The use of stabilized fly ash as a quarry fill has been proposed by the LAMS team, as an alternative to the conventional clay liner and cover systems suggested by Golder Associates/1,5/. Recent studies conducted by the Civil Research Department of the Ontario Hydro Research Division indicate that the environmental impact of fly ash can be significantly reduced by cement-stabilization/6,7,8/. Cement addition apparently encapsulates the fly ash particles, thereby reducing the release of contaminants/6/. Although cement stabilization of fly ash may be beneficial from an environmental point of view, the cost of such a method must also be considered.

For this report, the costs of the containment designs proposed by Golder Associates are compared to the costs of utilizing cement-stabilized fly ash (CSFA) with less rigorous containment/1,5/. Using available data, the environmental impacts of these alternatives were also compared to the impact of the original containment designs proposed by Golder Associates. The assumptions and methods used to reach these conclusions are also presented. During the examination of quarry filling costs, it was found that an impermeable geomembrane might prove to be less expensive than the proposed clay containment material. This finding is also presented in the report.

Prior to the comparison, some background on the regulations governing fly ash disposal, the proposed fly ash containment systems, and the leaching behaviour of fly ash is given. This is done in order to establish common ground for a comparison.

2.0 DISPOSAL GUIDELINES/REGULATIONS

Using the Ontario Ministry of the Environment (MOE) Regulation 309 criteria, Ontario Hydro coal ash is classified as a non-hazardous, non-registerable waste/9/. The Environmental Protection Act requires that certain measures be used during disposal or utilization of coal fly ash to ensure that environmental impact is minimized.

Fly ash disposal at the Lincoln Quarry or the Uhtoff Quarry will take place below the water table, and the ash will eventually be fully submerged below proposed recreational lakes. It has been noted by Golder Associates that this may appear to be in conflict with lakefilling guidelines/1/. Lakefilling guidelines require that a "Restricted" lakefill must satisfy the following two criteria/10/:

a) Meet the Decommissioning Guidelines for Soil for Agricultural/Residential/Parkland Use (MOE Policy 14-17-01) (Bulk Chemical Analysis).

b) Meet the Ontario Drinking Water Objectives (ODWO) in Waste Regulation 309, Schedule IV Leach Test.

Unstabilized fly ash does not meet the lakefilling guidelines, however, the conditions under which the fly ash will be placed, and the time before complete submergence are quite different from conventional lakefilling operations. Unlike lakefilling, fly ash quarry fill will be placed in a dry state, and exposed to weathering for several years prior to submergence.

Bulk chemical analysis has shown that fly ash contains some elements in quantities greater than the Decommissioning Guidelines for Soil for Agricultural/ Residential/ Parkland Use (MOE Policy 14-17-01). This is illustrated in Table I. The only apparent way to meet this guideline is to alter the chemical composition of the fly ash with the addition of a chemically inert material. Cement addition will make the chemical composition of CSFA different from that of unstabilized fly ash, however, only small quantities (5 to 10 percent by weight) of cement are added for stabilization purposes. The cement may also chemically react with the contaminants in the fly ash, altering their properties. Therefore, most of the contaminants

in fly ash may not be in a leachable form. Further investigations are needed to better understand the effects of cement stabilization of fly ash.

Quarry filling with fly ash at the Cayuga Quarry will be done completely above the water table, and should remain permanently above the water table. For the quarry filling operation at the Cayuga Quarry, the MOE's Reasonable Use Policy is applicable/1/. The MOE's Reasonable Use Policy sets guidelines for the maximum acceptable concentration levels down gradient of the disposal site. Lowering the contaminant concentrations in leachate by cement stabilization would improve the probability of meeting these guidelines.

The leaching of contaminants from fly ash is the principal environmental concern. Therefore, environmental impact assessment, for fly ash disposal, should focus on the leaching and migration of contaminants. A reduction in the release of contaminants from fly ash, by cement stabilization, should increase the probability of gaining environmental approval.

3.0 FLY ASH LEACHING

Most trace elements and other minor constituents that leach from Ontario Hydro coal fly ash are not at a significant concentration to be of concern. Certain chemical constituents, however, have been identified as the critical contaminants in bituminous coal ash leachate. These include: arsenic, boron, chromium, selenium, and sulphate/1/.

In some situations other contaminants may also be a concern. In areas of acidic soil where water is to be used for irrigation or livestock watering, a maximum vanadium concentration of 0.1 mg/L has been recommended/11/. For each of the candidate quarries, an analysis of groundwater revealed alkaline conditions/1/. These alkaline conditions are likely due to the formation geology. For these conditions, a vanadium concentration of 1.0 mg/L should be acceptable/11/. Therefore, vanadium is not a critical contaminant.

With the implementation of flue gas cleaning (FGC) systems at Ontario Hydro's coal-fired generating stations, the chemistry of the fly ash is expected to change/12/. Recent chemical analyses have indicated that ammonia and fluoride are potential contaminants of concern in fly ash leachate/12/. This is a factor that requires consideration in future studies, however, it is not included in this comparison of containment systems.

A number of field and laboratory studies have been used to investigate the leaching behaviour of fly ash and stabilized fly ash/6,7,8,9/. These studies have indicated that cement addition can cause a drastic reduction in the release of contaminants from fly ash. Data on the leaching behaviour of fly ash and cement-stabilized fly ash is given below, in order to illustrate this observation.

3.1 Unstabilized Fly Ash

Leaching data for unstabilized fly ash has been obtained from Ontario Ministry of the Environment (MOE) Regulation 309 (Reg. 309) leach tests, distilled water leach tests, column leaching experiments, and groundwater sampling at coal ash disposal sites/9/. This data has helped develop a better understanding of the mechanisms controlling the leaching of contaminants from fly ash.

3.1.1 Field Data

Table II shows the contaminant concentrations observed in pore water samples collected from various fly ash disposal sites/9/. The majority of the contaminant concentrations shown in Table II are below the ODWO. Concentrations of the critical contaminants are, however, above these objectives. A reduction in the concentration levels of these critical elements is a primary objective of fly ash stabilization.

3.1.2 Laboratory Data

The results of Reg. 309 leaching tests show trends in contaminant release that are similar to those observed in the analyses of pore water from fly ash disposal sites. Most contaminant levels observed in Reg. 309 tests are, however, higher than those observed in the pore water from the fly ash disposal sites. This indicates that the Reg. 309 test represents leaching under severe conditions. The results of Reg. 309 tests on unstabilized fly ash are shown on Table III.

It can be seen from these test results that the majority of the observed contaminant concentrations are below the ODWO. Only 7 contaminants: arsenic, barium, boron, cadmium, chromium, selenium, and uranium exceed the MOE Schedule 4 criteria.

3.2 Cement-Stabilized Fly Ash

The Civil Research Department of Ontario Hydro's Research Division has been investigating the leaching behaviour of cement-stabilized fly ash since 1989/6,7,8/. This research has investigated the effects of cement stabilization on the leaching behaviour of fly ash. Static and dynamic leaching tests were used to study contaminant release from samples stabilized with 5, 10, 15, and 20 percent, by weight, type 10 Portland cement. This laboratory testing has indicated the following:

1) Cement stabilization of fly ash reduces the amount of contaminants that are available in a leachable form /6,7,8/.

2) Maximum concentrations of most contaminants observed in static leaching tests are lowered by cement stabilization of the fly ash/6,7,8/.

3) There is very little decrease in the maximum concentrations of contaminants observed in static leaching tests when cement addition is increased beyond 10% by weight/6,7/.

It is hypothesized that the cement paste coats the surface of the fly ash particles and the coating appears to physically and chemically bind the contaminants to the fly ash. This results in a reduction of the contaminant release into solution/8/.

3.2.1 Field Data

Field data on the production of leachate from cement-stabilized fly ash as a result of contact with water is limited. Studies done by Detroit Edison have indicated that cement-stabilized flowable fly ash, placed directly in water, had little impact on water quality/13/. Contaminant concentration levels were monitored during the placement of a CSFA slurry in a bottom ash storage basin. Water flowed through the basin, so both basin intake water and basin effluent were analyzed for contaminants. Water samples were taken daily, for twelve days, during the month-long filling operation. The filling operation consisted of the construction of a trial peninsula 50 metres long and 9 metres wide, in water that ranged in depth from 2 to 6 metres. Water flowing through the basin impinged on, travelled along the side, and around the tip of the peninsula at a rate of about 0.6 m/s. The results of monitoring of the ash basin intake water and effluent, both prior to and during filling, are presented on Table IV/13/. It can be seen on Table IV that the monitoring results are inconclusive, as contaminant levels varied significantly. Also, this study may not be directly applicable to the proposed quarry filling operation, as the fly ash will be placed above water, and later submerged (Lincoln and Uhtoff).

Leachate production from a highway shoulder composed of type F fly ash with 10% cement has been monitored as part of an EPRI demonstration project in Michigan/14/. Leachate production from this stabilized highway shoulder could be similar to that which would develop in a quarry fill composed of stabilized ash. The contaminant levels in pore water from Lakeview fly ash disposal sites are compared to the contaminant levels in leachate from the stabilized highway shoulder. Table V shows this comparison. While the ash sources are different, they indicate that contaminant levels in a stabilized fly ash leachate are lower than those in unstabilized fly ash. The lower contaminant concentration levels in the stabilized ash may also reflect lower contaminant levels in the fly ash prior to stabilization. Leaching data from unstabilized Michigan fly ash was not reported/14/.

The two examples described above provide very little information on the field leaching behaviour of CSFA. In order to gain a better understanding of the field leaching behaviour of Ontario Hydro CSFA, some sort of field monitoring program would have to be conducted. This program would give a better understanding of the field behaviour of a CSFA quarry fill.

3.2.2 Laboratory Data

The reduction in contaminant release, due to cement stabilization of fly ash, has been studied through the use of laboratory leaching tests with distilled water/6,7,8/. A description of these leaching tests can be found elsewhere/6,7/. Results from these tests clearly indicate that cement stabilization causes a drastic reduction in the release of most of the critical contaminants from fly ash. The reduction of contaminant release from cement-stabilized fly ash versus unstabilized fly ash is shown in Figure 1, and summarized on Table VI.

Chromium appears to be the only exception to the behaviour noted above. Cement addition causes chromium levels to increase slightly. This increase is likely due to a change in pH caused by cement addition, and cannot be attributed to chromium release from the Portland cement. This same trend can be observed when the results of distilled water leach tests are compared to Reg. 309 leach tests /9/. Chromium levels are higher in distilled water leach test results where the pH is typically higher than the Reg. 309 tests/9/. The increase in chromium release observed in the laboratory leaching tests, due to cement addition, is relatively minor/7/.

Laboratory leaching tests also indicate that the mass of contaminants leaching from CSFA is less than the mass of contaminants leaching from unstabilized fly ash. Cumulative fractional release (CFR) is a measure of the percentage of the total mass of a contaminant that has leached from a sample. Table VII/8/ shows the effect of cement addition on the CFR for a static leach test of about 100 days. From the table, it is clear that cement addition reduces the amount of contaminants leaching from CSFA. Further research, however, would be necessary to define the effect of cement stabilization on the contaminating lifespan of fly ash.

Leaching of contaminants from cement-stabilized fly ash has also been studied using standardized leach tests. The U.S. EPA Method 1310 leaching test (similar to Reg. 309) has been used on 10% cement-stabilized Michigan fly ash /14/ and the Reg. 309 leaching test has been used to examine unstabilized and 10% cement-stabilized samples of fly ash from Lakeview TGS and Nanticoke TGS. These test results show that cement stabilization significantly reduces contaminant release, and only the concentrations of barium, boron, and selenium in the cement-stabilized fly ash leachate from the Reg. 309 test exceed the ODWO (similar to MOE schedule 4). Chromium exceeds the ODWO for stabilized Nanticoke fly ash. Table VIII contains a summary of the results of these tests.

Tests following the MOE Reg. 309 leach test procedure, but with distilled water as the leachant, have also been done on unstabilized and 10% cement-stabilized fly ash from Lakeview TGS and Nanticoke TGS. These test results show contaminant levels that are below those observed when an acidic reagent is used for leaching. The results of these tests are summarized on Table IX. Contaminant concentrations are significantly lower for the cement-stabilized fly ash. When distilled water is used for the test, only the concentration of selenium in the cement-stabilized Lakeview fly ash leachate exceeds the ODWO.

The concentration of chromium is equal to the ODWO for the 10% cement stabilized fly ash from both Lakeview TGS and Nanticoke TGS.

4.0 PROPOSED FLY ASH CONTAINMENT DESIGNS

In order to examine the costs and environmental impact of fly ash disposal versus cement-stabilized fly ash disposal, it is necessary to examine the proposed containment systems. Each component of the containment systems is identified and its function is described. This is necessary to define material quantities, and ultimately, containment costs.

A discussion of the components of the original containment systems and the stabilized fly ash containment systems proposed for the Lincoln and Cayuga quarries is presented. Except for fill geometry, the containment designs proposed for the Uhtoff quarry are identical to those proposed for the Lincoln quarry. Therefore, the descriptions of the Lincoln quarry original design and the Lincoln quarry cement-stabilized fly ash design also represent the Uhtoff quarry original design and the Uhtoff quarry cement-stabilized fly ash design, respectively. The Uhtoff quarry is not described separately, but is treated separately for the cost analysis, which appears later in this report.

4.1 Lincoln Quarry Original Design

The containment system proposed for the Lincoln quarry/1/ is a passive one; there is no apparent need for leachate collection and treatment. There are five basic components comprising this containment system: the base drainage layer, the filter layer, the clay liner/cover, the internal drainage layer, and the rip rap cover. Figure 2 shows the configuration of this containment system/5/. Each component has a function related to the pre- and post-flooding stages of the quarry filling operation.

The clay cover and clay liner system, and the internal drainage layer are unnecessary for normal quarry operation/1/. These components are required for a contingency plan to pump leachate from the fly ash for treatment. The contingency plan will be implemented only if contaminant migration from the fly ash is having a serious environmental impact on the water in which it is submerged. Fly ash stabilization could eliminate the need for the contingency plan, and these components of the containment system.

The other components of the containment design are primarily for water and erosion control. Prior to inundation of the quarry, the base drainage layer will act both as capillary break and a pathway, around the fly ash, for seepage. The rip rap layer is used to protect the fly ash from erosion due to wave action as the water level in the quarry gradually rises. The filter layer is used to prevent the migration of fine particles due to flowing water or particle "washout" by wave action.

4.2 Cayuga Quarry Original Design

Active leachate collection and treatment is required at the Cayuga quarry/1/. The components of this containment and collection system include: a basal levelling layer, a clay liner and cover, an internal leachate collection layer, a lateral drainage layer, a thermal layer, and a topsoil cover. Figure 3 shows the configuration of this containment system/5/. Each component is considered necessary for normal quarry operation. The function of each component is discussed briefly below.

All components of this containment system are required for control of the production and migration of water or leachate. The levelling layer at the base of the quarry fill will act as a capillary break, and provide a pathway, around the fly ash, for seepage. The clay cover and liner are needed to limit the formation and migration of fly ash leachate. The internal leachate collection layer is required for the collection of leachate for treatment. The lateral drainage layer is used to promote runoff across the clay cover. The function of the thermal layer is to prevent frost heave damage to the clay cover. The topsoil cover will be vegetated to prevent erosion of the upper containment layers and promote the evapotranspiration of rainwater.

4.3 Lincoln Quarry - Cement-Stabilized Fly Ash

Diffusion will be the controlling transport mechanism for contaminants from the submerged fly ash, and stabilization appears to lower diffusion rates. The lower levels of contaminant migration from cement-stabilized fly ash allow a different approach to disposal to be taken. Three factors were considered when the containment of submerged stabilized fly ash was examined. These factors are:

1) Submerged cement-stabilized fly ash will have little impact on water quality. Therefore, there is no need for a contingency to remove and treat the leachate.

2) A clay barrier would delay and reduce the environmental impact, as it would adsorb some contaminants.

3) Stabilized fly ash does not have enough strength to withstand erosion. A rip rap cover is necessary.

Based upon these factors, two containment designs utilizing stabilized fly ash are proposed for the Lincoln quarry. These containment designs are similar to those proposed for unstabilized fly ash, however, the contingency plan has been excluded. It is estimated that contaminant migration from stabilized fly ash will be significantly low that a contingency plan is unnecessary. Leaching from a CSFA quarry fill is discussed later in this report.

The first design proposed for stabilized fly ash containment utilizes the following components: a filter layer, a clay cover/liner, and rip rap. This containment system is similar to that proposed for unstabilized fly ash, except that the internal and external drainage

layers have been eliminated. Figure 4 shows the configuration of this containment system. The clay cover/liner material will be in intimate contact with the stabilized ash, and should provide an adsorption barrier and delay contaminant migration. The adsorption barrier provides additional protection against possible contamination of the water.

The second design proposed for stabilized fly ash containment utilizes only a filter layer and a layer of rip rap. This design assumes that the hydraulic conductivity of the stabilized fly ash (10^{-8} m/s) should be low enough to limit excessive rainwater infiltration and leachate production/15/. A clay cover/liner is not considered to be necessary for either the control of water infiltration or control of contaminant migration. Figure 5 shows the configuration of this proposed containment system. The filter layer and rip rap cover are needed to control erosion of the stabilized fly ash.

4.4 Cayuga Quarry - Cement-Stabilized Fly Ash

The advective movement of water through the fly ash will be the principal means of contaminant transportation. Due to this factor, the control of water movement through the fly ash will greatly restrict leachate migration. Two methods of containment have been proposed for the use of stabilized fly ash at the Cayuga quarry.

The first method of containment is identical to the Cayuga original design. Stabilized fly ash is substituted for the unstabilized fly ash, and contaminant release is expected to be reduced. This reduction would be due to a decrease in the concentration of contaminants in the leachate from the stabilized fly ash. Figure 6 shows the configuration of this proposed containment design.

The second method of containment is similar to the Cayuga original design, except that no clay cover/liner is used. The low hydraulic conductivity of the stabilized fly ash (10^{-8} m/s) would be exploited as a low permeability barrier. The concentration of contaminants in the leachate would be lower, however, there may be an increase in leachate production because the fly ash may be more permeable than a clay barrier. The configuration of this proposed design is shown in Figure 7.

4.5 Containment Materials

Locations, close to the candidate disposal sites, have been identified as possible sources for the natural materials needed to construct the proposed cover and liner systems/5/. The quantity and quality of available materials, however, have not been verified. Local material sources are preferred, in order to minimize haulage costs or the expense of establishing a borrow pit.

For cost comparison purposes, it is important to define the materials that will be used in these containment systems and their source. The materials comprising each component of the containment systems and their source are summarized on Table X/5/.

5.0 STABILIZED FLY ASH QUARRY FILLING

The use of cement-stabilized fly ash as a quarry fill requires the mixing and placement of the fly ash, a stabilizing agent, and water. There are several ways to mix and place cement-stabilized fly ash. The mixing and placement methods recommended for fly ash quarry filling are presented below.

5.1 Stabilized Fly Ash Mixing

Two methods, bulk mixing and mix-in-place, have been used previously to mix stabilized fly ash. The mix-in-place technique is commonly used for soil amendment, or mixing additives with materials that are already in place. Bulk mixing provides a more homogeneous mixture and is normally used to mix materials that have not been placed. Since the Lakeview fly ash will be loaded and unloaded during transportation to the placement site, it will be available for bulk mixing.

Bulk mixing is recommended for the proposed quarry filling operations. There are several "ready-mix" plants near the quarries with capacities of approximately 1000 m^3/day. The operators of several of these plants were contacted to determine the possibility of using their facilities to mix fly ash and cement, and the approximate cost/16/. These operators were unable to supply exact unit costs for mixing, or information about the availability of the mixers for this purpose. A pug-mill mixer, at the site, was identified as an alternate mixing method.

The "pug-mill" or continuous-type mixer has been used successfully on several stabilized fly ash projects that are reported in the literature/14,17,18/. The production rates of these mixers can be 1000 m^3 per day, and relatively good quality control can be achieved. Field sampling and testing during a highway demonstration project with stabilized fly ash has shown that reasonably good quality control can be achieved with a pug-mill-type mixer /14/.

The cost of a pug-mill mixer with an output capacity of approximately 1000 m^3 per day was obtained from a U.S. supplier/19/. The capital cost of this mixer is approximately $110,000 (CDN). At least one operator is required to run the mixer/19/.

5.2 Stabilized Fly Ash Placement

The placement of stabilized fly ash will be similar to unstabilized fly ash. The fly ash will be stabilized by mixing with cement, at the site. The cement-stabilized ash will then be spread and compacted using conventional equipment. The only foreseen difference is that the stabilized ash would be placed/compacted at a higher moisture content. A moisture content of approximately 25% to 30% should be suitable for stabilized fly ash compaction, and also allow for curing of the cement/14/. There is no expected difference in the cost between the placement and compaction of unstabilized fly ash and the placement and compaction of stabilized fly ash.

6.0 QUARRY FILLING COSTS

The costs of the containment systems proposed by Golder Associates are compared to the costs of the systems using cement-stabilized fly ash/2,5/. The cost of the various containment designs only considers the tipping fees, material costs, hauling costs, and placement costs. Overhead costs associated with quarry preparation, security, fly ash haulage and placement, and other operating costs are not considered in the analysis. These costs would likely be identical, regardless of the filling method used/20/.

Tipping fees used in the analyses are $15.00/Mg at the Lincoln quarry and Uhtoff quarry, and $1.70/Mg at the Cayuga quarry/20/.

Factors considered in the determination of the costs for quarry filling include the following:

1) Clay and fill costs will vary with distance hauled. A fixed distance (8 miles, round trip) and fixed cost ($16.63/$Yd^3$, $21.75/$m^3$) is used for haulage, placement, and compaction of all imported materials.

2) Gravel costs are fixed, since they will be sourced at the sites.

3) Clay and fill will be compacted.

4) $1.00 US = $1.17 CDN.

5) Material volumes estimated by Golder Associates /5/ are used.

6) 1 yd^3 = 0.765 m^3

7) 1 m^3 fly ash = 1 Mg

8) Unit weights of materials are estimated from Navfac Manual/21/.

9) Rates for bulk portland cement, delivered, were found to be $131.65 per tonne to St. Catherines, and $133.45 per tonne to Orillia /22/. A Portland cement cost of $132 per tonne was used for the comparisons.

10) A cost of $0.78 per m^3 was added to the material cost of cement stabilized fly ash to allow for mixing equipment and operating costs.

Leachate treatment costs are not considered here. A significant reduction in the quantity of contaminants available for leaching is realized when fly ash is stabilized/7,8/. For similar containment systems, however, the use of stabilized fly ash does not preclude the need for leachate treatment. For example, environmental impact analyses indicate that leachate treatment is still required at the Cayuga quarry, even if stabilized fly ash is used.

The cost savings due to a reduction in the time required to gain environmental approval might also be achieved if cement-stabilized fly ash is used. This is due to the fact that cement-stabilized fly ash will have less of an impact on the environment. This figure is difficult to estimate, and, therefore, not considered as part of the analysis.

Based upon these assumptions, the costs of the various containment designs have been calculated. Only the construction costs have been considered in the comparisons. These costs are summarized below.

6.1 Lincoln Quarry

The costs for the construction of the proposed fly ash containment systems at the Lincoln quarry were determined from Tables XI and XII to be the following:

a)	Lincoln Original	$ 57,615,286
b)	Lincoln Stabilized (5% cement) - clay, sand, rip rap	$ 64,887,752
c)	Lincoln Stabilized (10% cement) - clay, sand, rip rap	$ 79,587,572
d)	Lincoln Stabilized (5% cement) - sand, rip rap	$ 54,013,567
e)	Lincoln Stabilized (10% cement) - sand, rip rap	$ 68,713,567

From this analysis, option "d" is the least expensive, followed by option "a". Fly ash stabilized with approximately 5% cement appears to be an economically feasible option for fly ash disposal at the Lincoln Quarry. The reason for this cost difference is the tremendous savings in material costs and tipping fees realized by option "d".

6.2 Cayuga Quarry

The costs for the construction of the proposed fly ash containment systems at the Cayuga quarry were determined from Tables XIII and XIV to be the following:

a)	Cayuga Original	$ 23,902,681
b)	Cayuga Stabilized (5% cement) - clay cover/liner	$ 37,076,054
c)	Cayuga Stabilized (10% cement) - clay cover/liner	$ 50,446,054
d)	Cayuga Stabilized (5% cement) - no clay cover/liner	$ 28,654,744
e)	Cayuga Stabilized (10% cement) - no clay cover/liner	$ 42,024,744

From this analysis, option "a" is the least expensive, followed by option "d". Cement stabilization does not appear to be a viable option for the Cayuga quarry. The high cost of cement, the low tipping fee, and the need for minimized leachate migration resulted in the original design being the most economical. If the tipping fee is increased, then stabilized fly ash might become more competitive.

6.3 Uhtoff Quarry

The costs for the construction of the proposed fly ash containment systems at the Uhtoff quarry were determined from Tables XV and XVI to be the following:

a)	Uhtoff Original	$ 98,223,935
b)	Uhtoff Stabilized (5% cement) - clay, sand, rip rap	$ 93,206,755
c)	Uhtoff Stabilized (10% cement) - clay, sand, rip rap	$107,906,755
d)	Uhtoff Stabilized (5% cement) - sand, rip rap	$ 69,544,050
e)	Uhtoff Stabilized (10% cement) - sand, rip rap	$ 84,244,050

From this analysis, option "d" is the least expensive, followed by option "e". Cement stabilization can result in a tremendous savings due to a decrease in the need for extensive containment materials. The cost of materials for containment is enormous due to the high tipping fee and the fill geometry.

6.4 Geosynthetic Containment

While not directly related to the comparison of unstabilized versus stabilized fly ash, it was noted during cost comparisons that geosynthetic materials might provide less expensive containment than natural materials. The proposed tipping fees to be levied on all materials dumped in the quarry, greatly increases the cost of clay containment. A tremendous savings might be realized by using geosynthetics.

A comparison of the cost of an impermeable geosynthetic (geomembrane) versus the cost of a clay barrier was done. The cost of a geosynthetic barrier has been estimated to be between $6 and $10 per m^2 /23/. For this comparison $10 per m^2 was used. The cost savings of replacing the clay covering layer with a geomembrane, for the original design, at each quarry is shown on Table XVII. The cost differences on Table XVII do not include the tipping fees for the geomembrane, however, the weight of the geomembrane is so low (30 to 60 times less than the natural materials) that the tipping fee would be negligible.

The savings are directly evident on a materials cost basis, however, geosynthetics might also provide a further reduction in cost savings because there is no need to maintain strict quality control during the placement and compaction of materials. Monitoring the in situ properties of natural materials during placement is a costly procedure that may be eliminated by the use of geosynthetics.

It is estimated that geosynthetic containment costs could be one half to one quarter of the costs of the natural containment materials that are proposed.

7.0 ENVIRONMENTAL IMPACT

Laboratory leaching tests on fly ash indicate that cement stabilization of fly ash reduces contaminant release. In this section, analytical and numerical methods are used to show that the environmental impact of quarry filling can be reduced by the use of stabilized fly ash as a quarry fill. These methods of analysis are discussed briefly below.

The first method of analysis used is the water/chemical balance technique. The water balance values for the unstabilized fly ash, determined by Golder Associates/1/, were used for the cement-stabilized fly ash, to conduct an impact analysis for each of the three quarries. Contaminant levels from pore water analyses at unstabilized fly ash disposal sites/1/ and contaminant values from static leaching tests on cement-stabilized fly ash were used to determine the effects of quarry filling on local water quality/8/. These values were shown previously on Table VI.

On Table VI it can be seen that the contaminant concentrations from the static leaching tests are not directly comparable to the contaminant concentrations observed from field sampling of unstabilized fly ash disposal sites. For unstabilized Lakeview fly ash, under static leaching conditions, the concentrations of selenium and chromium are much higher than the maximum concentrations observed in the Lakeview pore water. Conversely, the concentrations of sulphate and boron observed in the static leaching tests on unstabilized Lakeview fly ash are below the minimum concentrations observed in the Lakeview pore water. Therefore, contaminant concentration reductions caused by the cement-stabilization appear to be masked by the test conditions. It is also possible that the fly ash used for the static leaching tests was not representative of bulk ash chemistry. These observations illustrate previous findings that it is difficult to accurately estimate, from laboratory tests, the characteristics of the leachate that will be generated in a disposal site/24/.

It has also been noted, however, that laboratory leaching tests do provide valuable information about fly ash leachate characteristics/24/. In terms of leaching from CSFA, it has been hypothesized that static leaching tests performed on pulverized samples represent extreme conditions/8/. The concentrations of contaminants which would develop in waters in contact with the sample would approach a maximum value/8/. In the laboratory tests, leaching from the source would likely be the only reaction. In the field, however, there could also be adsorption and precipitation. A better understanding of the controlling reactions could only be obtained through further laboratory and field testing. Until further testing has been conducted only the available data can be utilized. The field data for unstabilized Lakeview fly ash and the static leaching data from pulverized Lakeview CSFA are used for the analyses.

An analysis of the diffusive release of contaminants from the fly ash, after submergence, is the second method used to examine environmental impact. This analysis is only applicable to the Lincoln quarry and Uhtoff quarry, as they will be submerged after filling. For this analysis, diffusion coefficients for the critical contaminants were estimated from laboratory and field tests/8,11,25/. These coefficients are given on Table XVIII.

Like the chemical mass balance analysis used to determine groundwater impact, the diffusive analysis contains many assumptions. To obtain accurate diffusion coefficients, site specific data is required. Diffusion coefficients are a function of the tortuosity, bulk density, porosity and distribution coefficient of the medium/11/. The values given on Table XVIII have been determined from field measurements/25/, laboratory testing/8/ and estimation. If a detailed analysis of diffusive transport of contaminants from the fly ash is to be determined, then these site specific factors must be obtained.

Computer modelling of contaminant release and migration was the third method of analysis used to determine environmental impact. The computer model, GWPGM3/26/, was used to determine the effects of the various proposed containment designs on the release of contaminants to the environment.

The environmental impact of fly ash stabilized with 10% portland cement versus unstabilized fly ash contained within a conventional clay cover/liner system, utilizing these analysis methods, is given below.

7.1 Lincoln Quarry

Tables XIX to XXI show the existing hydrogeologic conditions at the Lincoln quarry and the expected contaminant concentrations due to fly ash leaching. The existing conditions were determined from the pumping rate of the quarry sump, meteorologic records, and estimates of groundwater discharge into the quarry/1/. A chemical mass balance analysis was used to determine the required sump flow to reduce the fly ash leachate concentration to an acceptable level/1/. These tables show that the required sump flow can vary, depending upon the contaminant of concern.

Overall, these results indicate that 10% cement-stabilized fly ash will have a lower impact on groundwater quality than the unstabilized fly ash. This is evident from the lower required sump flows for the stabilized fly ash. The only exceptions are the elements selenium and chromium. The concentration levels are higher for the CSFA than they are for unstabilized fly ash, for these two elements. This behaviour may be attributable to differences in the conditions under which the leachate concentrations used in the analysis were developed (field versus laboratory), or it may be due to variability in ash chemistry. This behaviour warrants further investigation.

Diffusive release of contaminants from the fly ash at the Lincoln quarry, due to quarry flooding, was also determined. This was done by assuming that diffusion would take place through a 1 m band of contaminant depleted material or natural soil. This method was previously used to examine the diffusive escape of contaminants from unstabilized fly ash/1/. Effective diffusivity values from Table XVIII were used in this analysis.

The results of these analyses indicate that 10% cement stabilization will significantly reduce the diffusive release of contaminants from the fly ash. The contaminant levels expected in the future recreational lake are well below the ODWO. This can be seen in Figures 8 and 9. If the diffusive release of contaminants from 5% cement-stabilized fly ash were plotted, it would likely lie somewhere between the unstabilized and the 10% stabilized fly ash. Investigation of diffusive release from 5% CSFA is required to verify this hypothesis.

7.2 Cayuga Quarry

Tables XXII to XXIV show the existing hydrogeologic conditions at the Cayuga quarry and the expected contaminant concentrations due to fly ash leaching. A chemical mass balance analysis was used to determine either the hydraulic conductivity required to lower the leachate contaminant concentrations to acceptable levels (Table XXII) or the downgradient contaminant concentrations at the property line (Tables XXIII and XXIV). The analyses shown on these tables represent a conservative estimate of the contaminant concentrations, as adsorption, precipitation, and other "sink-type" reactions are not considered. It would be difficult to estimate the sink-effect of the formations underlying the Cayuga quarry, without site specific sampling and testing.

The results of the analyses shown on Tables XXII to XXIV indicate that a liner and leachate collection system (LCS) would be required to limit leachate migration and to meet the MOEs Reasonable Use Policy at the property boundary. Even with a liner and LCS, the concentration of total dissolved solids (TDS) and sulphate for unstabilized fly ash exceed the limits allowed by the Reasonable Use Policy. For the CSFA, the concentration of chromium exceeds the limits allowed by the Reasonable Use Policy, at the property boundary.

7.3 Uhtoff Quarry

Tables XXV to XXVII show the existing hydrogoelogic conditions at the Uhtoff quarry and the expected contaminant concentrations due to fly ash leaching. Like the Lincoln quarry, the existing hydrogeologic conditions were determined, and a chemical mass balance analysis was used to calculate the sump flow required to reduce the fly ash leachate concentration to an acceptable level. These tables show the required sump flow for each of the contaminants of concern.

Overall, the results indicate that 10% cement-stabilized fly ash should have a lower impact on groundwater quality than the unstabilized fly ash. Again, the required sump flows for selenium and chromium for the CSFA are higher than those for the unstabilized fly ash, although they do not exceed the current sump flow rate. None of the required sump flow rates for the CSFA exceed the existing sump flow rate, whereas the required sump flow rate for unstabilized fly ash, for boron, exceeds the existing sump flow rate. It was noted previously that the observations in this analysis may be biased by a variability in ash chemistry or by the method which was used to derive the fly ash leachate concentrations

(field versus laboratory). Further investigations and testing would be required to gain a better understanding of this phenomenon.

Diffusive release of contaminants from the fly ash at the Uhtoff quarry, due to quarry flooding, was also determined. This was done by assuming that diffusion would take place through a 1 m band of contaminant depleted material or natural soil. This method was used to examine the diffusive escape of contaminants from unstabilized fly ash/1/. Effective diffusivity values from Table XVIII were used in this analysis.

The results of these analyses indicate that 10% cement stabilization will significantly reduce the diffusive release of contaminants from the fly ash. The contaminant levels expected in the future recreational lake are well below the ODWO. This can be seen in Figures 10 and 11. If the diffusive release of contaminants from 5% cement-stabilized fly ash were plotted, it would likely lie somewhere between the unstabilized and the 10% stabilized fly ash. Diffusive release of contaminants from 5% CSFA would have to be investigated to verify this hypothesis.

7.4 Numerical Modelling

Numerical modelling of the contaminant release from stabilized and unstabilized fly ash, in contact with water, has been conducted. This modelling is applicable to the submerged disposal schemes proposed for the Lincoln quarry and the Uhtoff quarry. Modelling results have shown the same behaviour as the laboratory tests and verified predictions used for the analytical analyses described above.

The computer model used was GWPGM3. This program was developed at the University of Waterloo to model contaminant leaching and migration in groundwater. This model has been used previously to examine contaminant migration from fly ash landfills/26/.

Computer modelling of the release of contaminants from the fly ash, during quarry flooding, showed that the cement-stabilized fly ash will have a lesser environmental impact than unstabilized fly ash. The modelling also indicated that a band of contaminant depleted material will be developed around the outer edge of the quarry fill. This corresponds to the assumptions and observations made during the previous analytical analysis of the fly ash.

A simulation of contaminant release from the original design has indicated that the clay surrounding the fly ash will adsorb some of the contaminants from the fly ash, and delay contaminant release. Eventually, however, the clay layer will become unable to adsorb contaminants. There will then be a "breakthrough" of contaminants. If stabilized fly ash is used, with no clay barrier, contaminant release will be immediate, however, it will be at a significantly lower concentration and rate of release. These effects are illustrated on Figure 12.

Numerical modelling of contaminant release and migration from stabilized and unstabilized fly ash, using the GWPGM3 computer program, is currently very useful for parametric analyses. Further calibration with laboratory and field data is necessary before it can be used to accurately predict field performance.

8.0 CONCLUSIONS

A lack of field data on the leaching of contaminants from CSFA precludes accurate determination of the environmental impact of quarry filling with CSFA. Sufficient data was, however, available to estimate environmental impact. The data utilized for CSFA came from static leaching tests on pulverized samples. These tests represent extreme leaching conditions for water in contact with the CSA and should yield a conservative estimate of the environmental impact of quarry filling with stabilized fly ash.

The laboratory leaching results from CSFA and field leaching results from unstabilized fly ash were used to compare the environmental impact of the quarry filling operations. Although this comparison is tenuous, it is the only option that is available until suitable field leaching data for CSFA can be obtained. Despite the use of leaching data from CSFA in extreme conditions, analyses conducted for this report indicate that CSFA will have a lesser environmental impact than unstabilized fly ash.

Investigations done for this report also showed that:

1) Cement-stabilized fly ash can be cost-competitive with the conventional containment systems that have been suggested for the proposed disposal sites.

2) More data concerning the geochemical behaviour of stabilized fly ash would allow for a more accurate determination of environmental impact.

4) Due to tipping fees levied on materials placed in the quarries, geosynthetics may prove to be more economical than natural materials as components of containment systems.

Stabilized fly ash appears to be a viable option for the disposal or utilization of fly ash. Cement stabilization of fly ash for disposal can be cost-competitive with the disposal of unstabilized fly ash under certain conditions, as follows:

1) Tipping fees are high, and the volume of containment materials can be reduced by fly ash stabilization.

2) Leachate treatment may be eliminated by ash stabilization, which reduces contaminant release.

The cost of cement-stabilized fly ash is high due to the price of portland cement. Mixing and placement of stabilized fly ash can be achieved for a relatively low cost. If a less expensive stabilizing agent could be identified, then stabilization would be a more attractive option.

The GWPGM3 computer model is valuable for parametric studies, however, it must be further calibrated before an attempt can be made to quantitatively predict field performance.

The use of geosynthetic materials for the containment of fly ash could be substantially less expensive than natural materials, especially in disposal sites with high tipping fees.

9.0 RECOMMENDATIONS

Further investigations should focus on alternative, low-cost, stabilizing agents. The price of portland cement is the primary cost in stabilized fly ash. If a less expensive alternative can be found, the cost of stabilized ash will be significantly reduced.

The chemical behaviour of stabilized ash needs to be further investigated, in order that the benefits of fly ash stabilization may be more clearly identified. A data base of leaching test results for stabilized fly ash with different additives and quantities of additives needs to be established. This would include, identifying the cumulative fractional release of contaminants from both stabilized and unstabilized fly ash, under identical leaching conditions, for both the laboratory and field environments. Ontario Hydro may then be able to estimate how much, and for how long, leachate will be released from an ash landfill.

The question of contaminating lifespan is an issue that was previously identified /1/, and still needs to be addressed. This could also be achieved through further studies of cement-stabilized fly ash.

Targets for leachate release should be clarified. Is it better to release a lesser amount of contaminants over a longer time or a greater amount over a shorter time period ? The MOE should be consulted on this matter.

Field performance of cement-stabilized fly ash should be investigated. This will also be valuable for calibration of the computer model. Calibration of the computer model would be useful for future applications.

The use of geosynthetic materials for the containment of fly ash leachate should be investigated further. Use of geosynthetics could represent a substantial cost savings in disposal sites with high tipping fees.

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TABLE I:

COMPARISON OF BULK CHEMICAL ANALYSIS
OF FLY ASH WITH MOE GUIDELINES

Element	MOE Guideline	Lakeview Fly Ash /9/	Avg. Fly Ash* (std. dev.)
Arsenic	25	89	89 (30%)
Cadmium	4	2.5	2.5 (25%)
Chromium (IV)	10	-	-
Chromium (total)	1000	170	137 (25%)
Cobalt	50	37	37 (10%)
Copper	200	96	84 (40%)
Lead	375	37	48 (25%)
Mercury	1	0.05	0.51 (35%)
Molybdenum	5	12	-
Nickel	200	99	35 (40%)
Selenium	2	5	14 (45%)
Silver	25	-	38 (30%)
Zinc	800	130	328 (25%)

* from various Ontario Hydro Coal Ashes /9/

Note: All values in ppm, except std. dev..

TABLE II:

RESULTS OF ANALYSES OF POREWATER FROM ASH DISPOSAL SITES

Element	*ODWO (mg/L)	Lakeview Porewater (mg/L)	Lambton Porewater (mg/L)	Nanticoke Porewater (mg/L)	Lakeview/ODWO (Exceedance Ratio)	Lambton/ODWO (Exceedance Ratio)	Nanticoke/ODWO (Exceedance Ratio)
Arsenic	0.05	0.044	0.037	0.012	0.880	0.740	0.240
Barium	1	0.03	-	-	0.030	-	-
Boron	5	28.6	-	3.62	5.720	-	0.724
Cadmium	0.005	0.0001	0.0004	-	0.020	0.080	-
Chloride	250	78.6	48	26	0.314	0.192	0.104
Chromium	0.05	0.08	0.0001	-	1.600	0.002	-
Copper	1	0.003	0.0167	-	0.003	0.017	-
Cyanide	0.2	0.005	-	-	0.025	-	-
Flouride	2.4	-	-	0.24	-	-	0.100
Iron	0.3	0.07	-	0.05	0.233	-	0.167
Lead	0.05	0.004	0.0027	-	0.080	0.054	-
Manganese	0.05	0.01	0.000017	0.02	0.200	0.000	0.400
Mercury	0.001	0.0001	-	-	0.100	-	-
Nitrate	10	7.4	-	1	0.740	-	0.100
Nitrite	1	0.17	-	-	0.170	-	-
Phenols	0.002	0.0005	-	-	0.250	-	-
PCB's	0.003	-	-	-	-	-	-
Selenium	0.01	0.028	0.01	0.01	2.800	1.000	1.000
Silver	0.05	0.0005	0.0005	-	0.010	0.010	-
Sulphate	500	2007	1743	294	4.014	3.486	0.588
Uranium	0.02	0.005	-	-	0.250	-	-
Radium-226	0.1	0.0037	-	-	0.037	-	-
Zinc	5	0.02	0.023	-	0.004	0.005	-
Tot. Disolved	500	3065	-	666	6.130	-	1.332

*ODWO = Ontario Drinking Water Objective

TABLE III:

RESULTS OF REG. 309 LEACH TESTS ON UNSTABILIZED FLY ASH

Element	MOE Schedule 4 (mg/L)	Lakeview Max. (mg/L)	Nanticoke Max. (pptr. ash) (mg/L)	Lakeview/ Schedule 4	Nanticoke Precipitator/ Schedule 4
Arsenic	0.05	0.05	0.166	1.000	3.320
Barium	1	0.5	5	0.500	5.000
Boron	5	15	23.4	3.000	4.680
Cadmium	0.005	0.035	0.005	7.000	1.000
Chromium	0.05	0.11	0.02	2.200	0.400
Cyanide	0.2	0.01	0.02	0.050	0.100
Flouride	2.4	1.8	0.36	0.750	0.150
Lead	0.05	0.005	0.002	0.100	0.040
Mercury	0.001	0.00032	0.0002	0.320	0.200
Nitrate	10	0.22	0.002	0.022	0.000
Nitrite	1	0.008	0.003	0.008	0.003
PCB's	0.003	0.001	0.0001	0.333	0.033
Selenium	0.01	0.05	0.09	5.000	9.000
Silver	0.05	0.002	0.0022	0.040	0.044
Uranium	0.02	0.03	0.047	1.500	2.350

TABLE IV /13/:

WATER QUALITY DATA OBTAINED PRIOR TO AND DURING THE PLACEMENT OF ASH-CEMENT FILL AT MONROE POWER PLANT

Parameter / Location	Cd	Li	Zn	Be	As	Cr	Pb	Se
Ash Basin Effluent Prior to Fill Placement	0.002* / 0.004	0.051 / 0.204	0.063 / 0.088	<0.001 / 0.001	0.007 / 0.022	0.012 / 0.052	0.003 / 0.006	0.008 / 0.017
Ash Basin Effluent During Fill Placement	<0.001 / 0.001	0.060 / 0.075	0.046 / 0.060	0.001 / 0.001	0.005 / 0.007	0.007 / 0.010	0.005 / 0.006	0.006 / 0.008
Intake Analyses Prior to Fill Placement	0.002 / 0.007	0.012 / 0.017	0.074 / 0.168	<0.001 / 0.002	0.010 / 0.066	0.013 / 0.052	0.004 / 0.007	0.005 / 0.019
Intake Analyses During Fill Placement	<0.001 / <0.001	0.014 / 0.037	0.035 / 0.039	<0.001 / 0.001	0.002 / 0.001	0.004 / 0.006	0.003 / 0.011	0.004 / 0.005

*Average Concentration mg/L
Max. Concentration mg/L

TABLE V:

COMPARISON OF ODWO, LAKEVIEW POREWATER, AND MAXIMUM LEACHATE CONCENTRATIONS OBSERVED IN MICHIGAN HIGHWAY DEMONSTRATION

Element	*ODWO (mg/L)	Lakeview Porewater (mg/L)	Max. Conc. from Michigan Highway Demo. Project (mg/L)
Arsenic	0.05	0.044	0.01
Chromium	0.05	0.08	0.03
Selenium	0.01	0.028	0.015

*ODWO = Ontario Drinking Water Objective

TABLE VI:

POREWATER ANALYSES RESULTS VERSUS STATIC LEACH TEST RESULTS

Chemical Element	From Lakeview Porewater Analysis		From Stabilized Ash Leaching Tests /5,6/		
	Mean	Range	Unstabilized	5% Cement	10% Cement
Sulphate	2007	1450 - 2400	600	450	430
Arsenic	0.044	0.012 - 0.067	0.05	0.028	0.025
Selenium	0.028	0.012 - 0.052	0.17	0.08	0.035
Boron	28.6	17.8 - 51	7	3	0.8
Chromium	0.08	<0.02 - 0.2	0.38	0.46	0.65

Notes: (1) All values are leachate concentration in mg/L
(2) Laboratory test results are from STATIC leaching tests on POWDERED samples.
(3) Water was used to leach laboratory specimens.

TABLE VII:

EFFECT OF CEMENT ADDITION ON CFR* OF CONTAMINANTS

Contaminant	*100% Fly Ash	*90% Fly Ash, 10% Cement
Arsenic	0.25	0.20
Boron	15.5	2.2
Selenium	9.5	2.8
Sulphate	42	13.5

* Cumulative Fractional Release (%),
100 day static leaching test
on pulverized samples.

TABLE VIII:

RESULTS OF MOE REGULATION 309 TESTS ON
STABILIZED AND UNSTABILIZED FLY ASH

	Michigan*		Lakeview		Nanticoke Precipitator		MOE
Element	Sample "A"	Sample "B"	10% Cement	0% Cement	10% Cement	0% Cement	Sched. 4
Arsenic	0.009	0.005	0.004 - 0.017	0.01 - 0.05	0.011	0.022 - 0.166	0.05
Barium	0.07	0.46	0.895 - 1.54	0.08 - 0.5	2.05	< 1.0 - 5.0	1
Boron	n.a.	n.a.	6.2 - 7.57	12.7 - 15	5.2	12.3 - 23.4	5
Cadmium	< 0.002	< 0.002	< 0.005	0.0051 - 0.035	< 0.005	< 0.005	0.005
Chromium	0.16	0.07	< 0.01 - 0.05	0.02 - 0.11	0.08	< 0.02	0.05
Copper	< 0.02	< 0.02	n.a.	0.005 - 0.05	n.a.	< 0.047 - 0.06	-
Lead	< 0.02	< 0.02	< 0.05	< 0.002 - 0.005	< 0.05	< 0.002	0.05
Mercury	< 0.0002	< 0.0002	< 0.0001	< 0.0001 - 0.00032	< 0.0001	< 0.0002	0.001
Selenium	0.024	0.014	0.0215 - 0.046	0.02 - 0.05	0.021	0.024 - 0.09	0.01
Silver	< 0.01	< 0.01	< 0.005	0.0005 - 0.002	< 0.005	0.0022	0.05
Zinc	< 0.02	< 0.02	n.a.	0.08 - 0.37	n.a.	0.05 - 0.24	-

* from Michigan Highway Demonstration Project /14/

Notes: 1) All values are in mg/L
2) n.a. = not analysed

TABLE IX:

RESULTS OF DISTILLED WATER REG. 309 LEACH TESTS*
ON STABILIZED AND UNSTABILIZED FLY ASH

Element	Lakeview		Nanticoke Lagoon		MOE
	10% Cement	0% Cement	10% Cement	0% Cement	Schedule 4
Arsenic	0.019	0.028 - 0.04	0.005	0.023 - 0.3	0.05
Barium	0.021	0.5	0.027	< 1.0	1
Boron	0.19	4.8 - 5.6	0.56	1.4 - 1.9	5
Cadmium	< 0.005	< 0.0001	< 0.005	< 0.0001	0.005
Chromium	0.005	0.14 - 0.22	0.05	< 0.05	0.05
Copper	n.a.	< 0.05	n.a.	< 0.001	-
Lead	< 0.05	< 0.002	< 0.05	< 0.0002	0.05
Mercury	< 0.0001	< 0.0002 - 0.00029	< 0.0001	< 0.0002	0.001
Selenium	0.024	0.03 - 0.054	0.009	0.019 - 0.035	0.01
Silver	< 0.005	< 0.0005 - 0.001	< 0.005	< 0.0002	0.05
Zinc	n.a.	0.02	n.a.	< 0.02	-

Notes: 1) All values are in mg/L
2) n.a. = not analysed

* No acetic acid was used for the extraction procedure.

TABLE X:

TYPES OF MATERIALS AND SOURCES OF CONTAINMENT SYSTEM COMPONENTS

Containment Component	Material Type	Source
Thermal cover Dyke Fill	General fill	Imported
Lateral Drainage Layer External Drainage Layer Internal Drainage Layer Leachate Collection Underdrain Blanket	3/4" Crushed Stone	On-Site
Filter Layer Levelling Layer	Sand	Imported
Clay Cover Clay Liner Dyke Clay Core	Clay	Imported
Erosion Protection	Rip Rap	On-Site
Topsoil	Loam	Imported

TABLE XI:

COST COMPARISON OF LINCOLN ORIGINAL AND ALTERNATE DESIGNS VERSUS STABILIZED FLY ASH SURROUNDED BY CLAY, SAND, AND RIP RAP

Material	Original (yd3)	Alternate (yd3)	Original (m3)	Alternate (m3)	Unit Weight (Mg/m3) *	Original (Mg)	Alternate (Mg)	Unit Cost** ($/Yd3)	Haulage Costs		Tipping Costs			Total Costs	
									Original	Alternate	Unit Cost($/Mg)	Original	Alternate	Original	Alternate
Ash			2000000	2000000	1	2000000	2000000				15	30000000	30000000	30000000	30000000
Clay	301000	269000	230132.259	205666.3	1.7	391224.8	349632.8	16.63	5005630	4473470	15	5868372.	5244492.	10874002	9717962.
Fill	0	783000	0	598649.6	1.85	0	1107501.	16.63	0	13021290	15	0	16612529	0	29633819
Gravel	165000	82100	126152.235	62770.29	1.85	233381.6	116125.0	23.8	3927000	1953980	15	3500724.	1741875.	7427724.	3695855.
Sand	97600	42000	74620.9584	32111.47	1.65	123124.5	52983.93	15.92	1553792	668640	15	1846868.	794759.0	3400660.	1463399.
Topsoil	0	125000	0	95569.87	1.3	0	124240.8	4.19	0	523750	15	0	1863612.	0	2387362.
Rip Rap	115000	14300	87924.285	10933.19	1.85	162659.9	20226.40	30.2	3473000	431860	15	2439898.	303396.1	5912898.	735256.1
					Totals	2910390.	3770710.		13960422	21072990		43655864	56560664	57615286	77633654

Total Cost (Original) 57615286
Total Cost (Alternate) 77633654

* Approximate unit weights, taken from NAVFAC, Design Manual 7.1
** Unit cost per cubic yard for 8 mile, round trip, haul and compaction, where needed.

Material	Volume (yd3)	Mass 10 percent (Mg)	5 percent (Mg)	Unit Cost ($/Mg)	Unit Cost** ($/Yd3)	Material Costs Stabilized Fly Ash		Tipping Costs Stabilized Fly Ash		Total Costs Stabilized Fly Ash	
						10 percent	5 percent	10 percent	5 percent	10 percent	5 percent
Cement		200000	100000	132		26400000	13200000	3000000	1500000	29400000	14700000
Ash		2000000	2000000	0		0	0	30000000	30000000	30000000	30000000
Clay	301000	391225	391225		16.63	5005630	5005630	5868375	5868375	10874005	10874005
Fill	0	0	0		16.63	0	0	0	0	0	0
Gravel	0	0	0		23.8	0	0	0	0	0	0
Sand	97600	123125	123125		15.92	1553792	1553792	1846875	1846875	3400667	3400667
Topsoil	0	0	0		4.19	0	0	0	0	0	0
Rip Rap	115000	162660	162660		30.2	3473000	3473000	2439900	2439900	5912900	5912900
					Totals	36432422	23232422	43155150	41655150	79587572	64887572

Total Cost (5 percent) 64887572 (with clay cover/liner, sand, and rip rap)
Total Cost (10 percent) 79587572 (with clay cover/liner, sand, and rip rap)

TABLE XII:

COST COMPARISON OF LINCOLN ORIGINAL AND ALTERNATE DESIGNS VERSUS STABILIZED FLY ASH SURROUNDED ONLY BY SAND AND RIP RAP

Material	Original (yd3)	Alternate (yd3)	Original (m3)	Alternate (m3)	Unit Weight (Mg/m3) *	Original (Mg)	Alternate (Mg)	Unit Cost** ($/Yd3)	Haulage Costs		Tipping Costs			Total Costs	
									Original	Alternate	Unit Cost($/Mg)	Original	Alternate	Original	Alternate
Ash			2000000	2000000	1	2000000	2000000				15	30000000	30000000	30000000	30000000
Clay	301000	269000	230132.259	205666.3	1.7	391224.8	349632.8	16.63	5005630	4473470	15	5868372.	5244492.	10874002	9717962.
Fill	0	783000	0	598649.6	1.85	0	1107501.	16.63	0	13021290	15	0	16612529	0	29633819
Gravel	165000	82100	126152.235	62770.29	1.85	233381.6	116125.0	23.8	3927000	1953980	15	3500724.	1741875.	7427724.	3695855.
Sand	97600	42000	74620.9584	32111.47	1.65	123124.5	52983.93	15.92	1553792	668640	15	1846868.	794759.0	3400660.	1463399.
Topsoil	0	125000	0	95569.87	1.3	0	124240.8	4.19	0	523750	15	0	1863612.	0	2387362.
Rip Rap	115000	14300	87924.285	10933.19	1.85	162659.9	20226.40	30.2	3473000	431860	15	2439898.	303396.1	5912898.	735256.1
					Totals	2910390.	3770710.		13959422	21072990		43655864	56560664	57615286	77633654

Total Cost (Original) 57615286
Total Cost (Alternate) 77633654

* Approximate unit weights, taken from NAVFAC, Design Manual 7.1
** Unit cost per cubic yard for 8 mile, round trip, haul and compaction, where needed.

Material	Volume (yd3)	Mass 10 percent (Mg)	5 percent (Mg)	Unit Cost ($/Mg)	Unit Cost** ($/Yd3)	Material Costs Stabilized Fly Ash		Tipping Costs Stabilized Fly Ash		Total Costs Stabilized Fly Ash	
						10 percent	5 percent	10 percent	5 percent	10 percent	5 percent
Cement		200000	100000	132		26400000	13200000	3000000	1500000	29400000	14700000
Ash		2000000	2000000	0		0	0	30000000	30000000	30000000	30000000
Clay	0	0	0		16.63	0	0	0	0	0	0
Fill	0	0	0		16.63	0	0	0	0	0	0
Gravel	0	0	0		23.8	0	0	0	0	0	0
Sand	97600	123125	123125		15.92	1553792	1553792	1846875	1846875	3400667	3400667
Topsoil	0	0	0		4.19	0	0	0	0	0	0
Rip Rap	115000	162660	162660		30.2	3473000	3473000	2439900	2439900	5912900	5912900
					Totals	31426792	18226792	37286775	35786775	68713567	54013567

Total Cost (5 percent) 54013567 (with sand and rip rap)
Total Cost (10 percent) 68713567 (with sand and rip rap)

TABLE XIII:

COST COMPARISON OF CAYUGA ORIGINAL AND ALTERNATE DESIGNS VERSUS STABILIZED FLY ASH WITH COMPLETE CLAY CONTAINMENT

Material	Original (yd3)	Original (m3)	Unit Weight (Mg/m3) *	Original (Mg)	Haulage Costs		Tipping Fees		Total
					Unit Cost**	Original	Unit Cost($/Mg)	Original	Original (CDN $)
Ash		2000000	1	2000000			1.7	3400000	3400000
Clay	447000	341757.8	1.7	580988.3	16.63	7433610	1.7	987680.2	8421290.2
Fill	169000	129210.4	1.85	239039.3	16.63	2810470	1.7	406366.9	3216836.9
Gravel	178000	136091.5	1.85	251769.2	23.8	4236400	1.7	428007.7	4664407.7
Sand	143000	109331.9	1.65	180397.6	15.92	2276560	1.7	306676.0	2583236.0
Topsoil	275000	210253.7	1.3	273329.8	4.19	1152250	1.7	464660.7	1616910.7
Rip Rap	0	0	1.85	0	30.2	0	1.7	0	0
			Totals	3525524.		17909290		5993391.	23902681.

Total Cost 23902681

* Approximate unit weights, taken from NAVFAC, Design Manual 7.1

** Unit cost per cubic yard for 8 mile, round trip, haul and compaction, where needed.

Material	Volume	Mass		Unit Cost ($/Mg)	Unit Cost** ($/Yd)	Material Costs		Tipping Costs		Total Costs	
		10 percent	5 percent			Stabilized Fly Ash		Stabilized Fly Ash		Stabilized Fly Ash	
	(yd3)	(Mg)	(Mg)			10 percent	5 percent	10 percent	5 percent	10 percent	5 percent
Cement		200000	100000	132		26400000	13200000	340000	170000	26740000	13370000
Ash		2000000	2000000	0		0	0	3400000	3400000	3400000	3400000
Clay	447000	581000	581000		16.63	7433610	7433610	987700	987700	8421310	8421310
Fill	169000	239040	239040		16.63	2810470	2810470	406368	406368	3216838	3216838
Gravel	178000	136091.5	136091.502		23.8	4236400	4236400	231355.5	231355.55	4467755.	4467755.
Sand	143000	180400	180400		15.92	2276560	2276560	306680	306680	2583240	2583240
Topsoil	275000	273330	273330		4.19	1152250	1152250	464661	464661	1616911	1616911
Rip Rap	0	0	0		30.2	0	0	0	0	0	0
				Totals		44309290	31109290	6136764.	5966764.5	50446054	37076054

Total Cost (5 percent) 37076054. (with clay cover/liner, and drainage)

Total Cost (10 percent) 50446054. (with clay cover/liner, and drainage)

TABLE XIV:

COST COMPARISON OF CAYUGA ORIGINAL AND ALTERNATE DESIGNS VERSUS STABILIZED FLY ASH WITH NO CLAY COVER

Material	Original (yd3)	Original (m3)	Unit Weight (Mg/m3) *	Original (Mg)	Haulage Costs		Tipping Fees		Total
					Unit Cost**	Original	Unit Cost($/Mg)	Original	Original (CDN $)
Ash		2000000	1	2000000			1.7	3400000	3400000
Clay	447000	341757.8	1.7	580988.3	16.63	7433610	1.7	987680.2	8421290.2
Fill	169000	129210.4	1.85	239039.3	16.63	2810470	1.7	406366.9	3216836.9
Gravel	178000	136091.5	1.85	251769.2	23.8	4236400	1.7	428007.7	4664407.7
Sand	143000	109331.9	1.65	180397.6	15.92	2276560	1.7	306676.0	2583236.0
Topsoil	275000	210253.7	1.3	273329.8	4.19	1152250	1.7	464660.7	1616910.7
Rip Rap	0	0	1.85	0	30.2	0	1.7	0	0
			Totals	3525524.		17909290		5993391.	23902681.

Total Cost 23902681

* Approximate unit weights, taken from NAVFAC, Design Manual 7.1

** Unit cost per cubic yard for 8 mile, round trip, haul and compaction, where needed.

Material	Volume	Mass		Unit Cost ($/Mg)	Unit Cost** ($/Yd)	Material Costs Stabilized Fly Ash		Tipping Costs Stabilized Fly Ash		Total Costs Stabilized Fly Ash	
	(yd3)	10 percent (Mg)	5 percent (Mg)			10 percent	5 percent	10 percent	5 percent	10 percent	5 percent
Cement		200000	100000	132		26400000	13200000	340000	170000	26740000	13370000
Ash		2000000	2000000	0		0	0	3400000	3400000	3400000	3400000
Clay	0	0	0		16.63	0	0	0	0	0	0
Fill	169000	239040	239040		16.63	2810470	2810470	406368	406368	3216838	3216838
Gravel	178000	136091.5	136091.502		23.8	4236400	4236400	231355.5	231355.55	4467755.	4467755.
Sand	143000	180400	180400		15.92	2276560	2276560	306680	306680	2583240	2583240
Topsoil	275000	273330	273330		4.19	1152250	1152250	464661	464661	1616911	1616911
Rip Rap	0	0	0		30.2	0	0	0	0	0	0
				Totals		36875680	23675680	5149064.	4979064.5	42024744	28654744

Total Cost (5 percent) 28654744. (with no clay layer)

Total Cost (10 percent) 42024744. (with no clay layer)

TABLE XV:

COST COMPARISON OF UHTOFF ORIGINAL AND ALTERNATE DESIGNS VERSUS STABILIZED FLY ASH SURROUNDED BY CLAY, SAND, AND RIP RAP

Material	Original (yd3)	Alternate (yd3)	Original (m3)	Alternate (m3)	Unit Weight (Mg/m3) *	Original (Mg)	Alternate (Mg)	Unit Cost**	Haulage Costs		Unit Cost ($/Mg	Tipping Costs		Total Costs	
									Original	Alternate		Original	Alternate	Original	Alternate
Ash			2000000	2000000	1	2000000	2000000				15	30000000	30000000	30000000	30000000
Clay	655000	292000	500786.145	223251.2	1.7	851336.4	379527.0	16.63	10892650	4855960	15	12770046	5692906.	23662696	10548866
Fill	0	854000	0	652933.3	1.85	0	1207926.	16.63	0	14202020	15	0	18118901	0	32320921
Gravel	438000	119000	334876.842	90982.52	1.85	619522.1	168317.6	23.8	10424400	2832200	15	9292832.	2524764.	19717232	5356964.
Sand	260000	55600	198785.34	42509.48	1.65	327995.8	70140.64	15.92	4139200	885152	15	4919937.	1052109.	9059137.	1937261.
Topsoil	0	171000	0	130739.5	1.3	0	169961.4	4.19	0	716490	15	0	2549421.	0	3265911.
Rip Rap	307000	15700	234719.613	12003.57	1.85	434231.2	22206.61	30.2	9271400	474140	15	6513469.	333099.2	15784869	807239.2
				Totals		4233085.	4018080.		34727650	23965962		63496285	60271203	98223935	84237165

Total Cost (Original) 98223935
Total Cost (Alternate) 84237165

* Approximate unit weights, taken from NAVFAC, Design Manual 7.1
** Unit cost per cubic yard for 8 mile, round trip, haul and compaction, where needed.

Material	Volume	Mass		Unit Cost ($/Mg)	Unit Cost** ($/Yd)	Material Costs		Tipping Costs		Total Costs	
						Stabilized Fly Ash		Stabilized Fly Ash		Stabilized Fly Ash	
	(yd3)	10 percent (Mg)	5 percent (Mg)			10 percent	5 percent	10 percent	5 percent	10 percent	5 percent
Cement		200000	100000	132		26400000	13200000	3000000	1500000	29400000	14700000
Ash		2000000	2000000	0		0	0	30000000	30000000	30000000	30000000
Clay	655000	851337	851337		16.63	10892650	10892650	12770055	12770055	23662705	23662705
Fill	0	0	0		16.63	0	0	0	0	0	0
Gravel	0	0	0		23.8	0	0	0	0	0	0
Sand	260000	328000	328000		15.92	4139200	4139200	4920000	4920000	9059200	9059200
Topsoil	0	0	0		4.19	0	0	0	0	0	0
Rip Rap	307000	434230	434230		30.2	9271400	9271400	6513450	6513450	15784850	15784850
				Totals		50703250	37503250	57203505	55703505	1.1E+08	93206755

Total Cost (5 percent) 93206755 (with clay cover/liner, sand, and rip rap)
Total Cost (10 percent) 107906755 (with clay cover/liner, sand, and rip rap)

TABLE XVI:

COST COMPARISON OF UHTOFF ORIGINAL AND ALTERNATE DESIGNS VERSUS STABILIZED FLY ASH SURROUNDED ONLY BY SAND AND RIP RAP

Material	Original (yd3)	Alternate (yd3)	Original (m3)	Alternate (m3)	Unit Weight (Mg/m3) *	Original (Mg)	Alternate (Mg)	Unit Cost**	Haulage Costs		Unit	Tipping Costs		Total Costs	
									Original	Alternate	Cost ($/Mg	Original	Alternate	Original	Alternate
Ash			2000000	2000000	1	2000000	2000000				15	30000000	30000000	30000000	30000000
Clay	655000	292000	500786.145	223251.2	1.7	851336.4	379527.0	16.63	10892650	4855960	15	12770046	5692906.	23662696	10548866
Fill	0	854000	0	652933.3	1.85	0	1207926.	16.63	0	14202020	15	0	18118901	0	32320921
Gravel	438000	119000	334876.842	90982.52	1.85	619522.1	168317.6	23.8	10424400	2832200	15	9292832.	2524764.	19717232	5356964.
Sand	260000	55600	198785.34	42509.48	1.65	327995.8	70140.64	15.92	4139200	885152	15	4919937.	1052109.	9059137.	1937261.
Topsoil	0	171000	0	130739.5	1.3	0	169961.4	4.19	0	716490	15	0	2549421.	0	3265911.
Rip Rap	307000	15700	234719.613	12003.57	1.85	434231.2	22206.61	30.2	9271400	474140	15	6513469.	333099.2	15784869	807239.2
				Totals		4233085.	4018080.		34727650	23965962		63496285	60271203	98223935	84237165

Total Cost (Original) 98223935
Total Cost (Alternate) 84237165

* Approximate unit weights, taken from NAVFAC, Design Manual 7.1
** Unit cost per cubic yard for 8 mile, round trip, haul and compaction, where needed.

Material	Volume	Mass		Unit Cost ($/Mg)	Unit Cost** ($/Yd)	Material Costs Stabilized Fly Ash		Tipping Costs Stabilized Fly Ash		Total Costs Stabilized Fly Ash	
	(yd3)	10 percent (Mg)	5 percent (Mg)			10 percent	5 percent	10 percent	5 percent	10 percent	5 percent
Cement		200000	100000	132		26400000	13200000	3000000	1500000	29400000	14700000
Ash		2000000	2000000	0		0	0	30000000	30000000	30000000	30000000
Clay	0	0	0		16.63	0	0	0	0	0	0
Fill	0	0	0		16.63	0	0	0	0	0	0
Gravel	0	0	0		23.8	0	0	0	0	0	0
Sand	260000	328000	328000		15.92	4139200	4139200	4920000	4920000	9059200	9059200
Topsoil	0	0	0		4.19	0	0	0	0	0	0
Rip Rap	307000	434230	434230		30.2	9271400	9271400	6513450	6513450	15784850	15784850
				Totals		39810600	26610600	44433450	42933450	84244050	69544050

Total Cost (5 percent) 69544050 (with sand and rip rap)
Total Cost (10 percent) 84244050 (with sand and rip rap)

TABLE XVII:

ESTIMATED COSTS OF GEOSYNTHETIC CONTAINMENT

Quarry (Original Designs)	Fill Dimensions			Surface Area* (S.A.) (m2)	Allowance For Sloped Fill Geometry (20% S.A.) (m2)	Total Estimated S.A. (m2)	Geosynthetic Unit Cost ($/10000 m2)	Total Geosynthetic Cost ($)	Total Clay Cost (Haul & Tip Fees) ($)	Estimated Savings if Geosynthetic Used ($)
	Length (m)	Width (m)	Height (m)							
Lincoln	400	225	22	112550	22510	135060	100000	1350600	5437001	4086401
Cayuga	330	400	15	147900	29580	177480	100000	1774800	4210645	2435845
Uhtoff	400	555	9	234195	46839	281034	100000	2810340	11831348	9021008

* Surface area of top, front, and 2 sides of fly ash fill.

TABLE XVIII:

EFFECTIVE DIFFUSION COEFFICIENTS (De) USED FOR ANALYSES

Element	De, Clay Material (m2/yr)	De, Stabilized Fly Ash (m2/yr)
Arsenic	0.000003784	0.00001766
Boron	0.0315386	0.000148219
Chromium	0.0315386	0.000148219
Selenium	0.000346896	0.00011353
Sulphate	0.031536	0.000160834

Notes: (1) De for As, B, Se, and SO4 from stabilized fly ash are from static leaching tests on monolithic samples /8/.

(2) De for Arsenic and Selenium,in clay, come from field measurements /9/.

(3) De for Boron, through clay, was determined from estimates of the free solution solution diffusion coeffiecient and soil tortuosity /1/.

(4) De for sulphate, through clay, was estimated to be similar to De for boron.

(5) De values for chromium, for clay and stabilized fly ash, were estimated to be similar to De for boron. This is conservative as boron is more soluble than chromium.

TABLE XIX:

LINCOLN QUARRY CHEMICAL MASS BALANCE ANALYSIS - AQUATIC LIFE CRITERIA

Geometric Variables:

Fill Length:	400 m
Fill Width:	225 m
Fill Height:	22 m
Fill Volume:	2.0E+06 m3

Meteorological Data:

Rainfall:	82 cm/yr
Evapotranspiration:	39 cm/yr

Sump Characteristics:

Sump Flow:	approx. 17200 cm3/s

Material Parameters:

Coal Ash Runoff Rate:	13 cm/yr
Seepage through Fly Ash:	30 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	PWQO (Aquatic Life) (mg/L)	Sump Water Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Required Sump Flow (cm3/s)
TDS	3065	N.A.	380	855	371	N.A.
SO4	2007	N.A.	63.9	855	371	N.A.
As	0.044	0.1	0.002	855	371	0
Se	0.028	0.1	0.001	855	371	0
B	28.6	N.A.	0.047	855	371	N.A.
Cr	0.08	0.1	0.01	855	371	0

Fly Ash Stabilized with 10% Cement

TDS	N.A.	N.A.	380	855	371	N.A.
SO4	430	N.A.	63.9	855	371	N.A.
As	0.025	0.1	0.002	855	371	0
Se	0.035	0.1	0.001	855	371	0
B	0.8	N.A.	0.047	855	371	N.A.
Cr	0.65	0.1	0.01	855	371	7492.222

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable.

TABLE XX:

LINCOLN QUARRY CHEMICAL MASS BALANCE ANALYSIS - DRINKING WATER OBJECTIVES

Geometric Variables:

Fill Length:	400 m
Fill Width:	225 m
Fill Height:	22 m
Fill Volume:	2.0E+06 m3

Meteorological Data:

Rainfall:	82 cm/yr
Evapotranspiration:	39 cm/yr

Sump Characteristics:

Sump Flow:	approx. 17200 cm3/s

Material Parameters:

Coal Ash Runoff Rate:	13 cm/yr
Seepage through Fly Ash:	30 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	DWO (mg/L)	Sump Water Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Required Sump Flow (cm3/s)
TDS	3065	500	380	855	371	26205.75
SO4	2007	500	63.9	855	371	4236.601
As	0.044	0.05	0.002	855	371	0
Se	0.028	0.01	0.001	855	371	2452
B	28.6	5	0.047	855	371	5841.631
Cr	0.08	0.05	0.01	855	371	919.5

Fly Ash Stabilized with 10% Cement

TDS	N.A.	500	380	855	371	N.A.
SO4	430	500	63.9	855	371	0
As	0.025	0.05	0.002	855	371	0
Se	0.035	0.01	0.001	855	371	3405.555
B	0.8	5	0.047	855	371	0
Cr	0.65	0.05	0.01	855	371	18390

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable.

TABLE XXI:

LINCOLN QUARRY CHEMICAL MASS BALANCE ANALYSIS - IRRIGATION WATER CRITERIA

Geometric Variables:

Fill Length: 400 m
Fill Width: 225 m
Fill Height: 22 m
Fill Volume: 2.0E+06 m3

Meteorological Data:

Rainfall: 82 cm/yr
Evapotranspiration: 39 cm/yr

Sump Characteristics:

Sump Flow: approx. 17200 cm3/s

Material Parameters:

Coal Ash Runoff Rate: 13 cm/yr
Seepage through Fly Ash: 30 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	PWQO (Irrigation Water) (mg/L)	Sump Water Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Required Sump Flow (cm3/s)
TDS	3065	N.A.	380	855	371	N.A.
SO4	2007	N.A.	63.9	855	371	N.A.
As	0.044	0.1	0.002	855	371	0
Se	0.028	0.02	0.001	855	371	516.2105
B	28.6	0.75	0.047	855	371	48569.13
Cr	0.08	0.1	0.01	855	371	0

Fly Ash Stabilized with 10% Cement

TDS	N.A.	N.A.	380	855	371	N.A.
SO4	430	N.A.	63.9	855	371	N.A.
As	0.025	0.1	0.002	855	371	0
Se	0.035	0.02	0.001	855	371	967.8947
B	0.8	0.75	0.047	855	371	87.19772
Cr	0.65	0.1	0.01	855	371	7492.222

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable.

TABLE XXII:

CAYUGA QUARRY CHEMICAL MASS BALANCE ANALYSIS - NO LINER

Geometric Variables:

Fill Length:	330 m
Fill Width:	400 m
Fill Height:	15 m
Fill Volume:	2.0E+06 m3

Meteorological Data:

Rainfall:	82 cm/yr
Evapotranspiration:	39 cm/yr

Aquifer Characteristics (Salina Formation):

Height of Mixing Zone:	10 m
Hydraulic Conductivity:	approx. 10.0E-03 cm/s
Local Flow Gradient:	0.0001

Material Parameters:

Coal Ash Runoff Rate:	13 cm/yr
Seepage through Fly Ash:	30 cm/yr
Downgradient Dilution Zone:	150 m
Dilution Zone Infiltration:	43 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	ODWO Reasonabl Use Conc. (mg/L)	Upgradient Groundwater Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Downgradient Infiltration Flow (cm3/s)	Required Groundwater Flow (cm3/s)	Corresponding Hydraulic Conductivity (cm/s)
TDS	3065	1474	1474	0.031	0.014	0.02	Infinite	N.A.
SO4	2007	917	917	0.031	0.014	0.02	Infinite	N.A.
As	0.044	0.013	0.001	0.031	0.014	0.02	0.09625	0.9625
Se	0.028	0.003	0.001	0.031	0.014	0.02	0.5425	5.4250
B	28.6	1.43	0.237	0.031	0.014	0.02	1.00485331	10.0485
Cr	0.08	0.02	0.01	0.031	0.014	0.02	0.25	2.5000

Fly Ash Stabilized with 10% Cement

TDS	N.A.	1474	1474	0.031	0.014	0.02	Infinite	N.A.
SO4	430	917	917	0.031	0.014	0.02	Infinite	N.A.
As	0.025	0.013	0.001	0.031	0.014	0.02	0.025	0.2500
Se	0.035	0.003	0.001	0.031	0.014	0.02	0.7	7.0000
B	0.8	1.43	0.237	0.031	0.014	0.02	0	0.0000
Cr	0.65	0.02	0.01	0.031	0.014	0.02	2.815	28.1500

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable.

TABLE XXIII:

CAYUGA QUARRY CHEMICAL MASS BALANCE ANALYSIS - WITH LINER AND CAP

Geometric Variables:

Fill Length:	330 m
Fill Width:	400 m
Fill Height:	15 m
Fill Volume:	2.0E+06 m3

Meteorological Data:

Rainfall:	82 cm/yr
Evapotranspiration:	39 cm/yr

Aquifer Characteristics (Salina Formation):

Height of Mixing Zone:	10 m
Hydraulic Conductivity:	approx. 10.0E-03 cm/s
Local Flow Gradient:	0.0001

Material Parameters:

Coal Ash Runoff Rate:	13 cm/yr
Seepage through Fly Ash:	30 cm/yr
Downgradient Dilution Zone:	150 m
Dilution Zone Infiltration:	43 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	ODWO Reasonabl Use Conc. (mg/L)	Upgradient Groundwater Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Downgradient Infiltration Flow (cm3/s)	Upgradient Groundwater Flow (cm3/s)	Concentration at Property Line (mg/L)
TDS	3065	1474	1474	0.0004	0	0.02	0.0001	1505.0439
SO4	2007	917	917	0.0004	0	0.02	0.0001	938.2683
As	0.044	0.013	0.001	0.0004	0	0.02	0.0001	0.0018
Se	0.028	0.003	0.001	0.0004	0	0.02	0.0001	0.0015
B	28.6	1.43	0.237	0.0004	0	0.02	0.0001	0.7904
Cr	0.08	0.02	0.01	0.0004	0	0.02	0.0001	0.0114

Fly Ash Stabilized with 10% Cement

TDS	N.A.	1474	1474	0.0004	0	0.02	0.0001	N.A.
SO4	430	917	917	0.0004	0	0.02	0.0001	907.4976
As	0.025	0.013	0.001	0.0004	0	0.02	0.0001	0.0015
Se	0.035	0.003	0.001	0.0004	0	0.02	0.0001	0.0017
B	0.8	1.43	0.237	0.0004	0	0.02	0.0001	0.2480
Cr	0.65	0.02	0.01	0.0004	0	0.02	0.0001	0.0225

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable.

TABLE XXIV:

CAYUGA QUARRY CHEMICAL MASS BALANCE ANALYSIS - WITH LINER, LCS, AND CAP

Geometric Variables:

Fill Length:	330 m
Fill Width:	400 m
Fill Height:	15 m
Fill Volume:	2.0E+06 m3

Meteorological Data:

Rainfall:	82 cm/yr
Evapotranspiration:	39 cm/yr

Aquifer Characteristics (Salina Formation):

Height of Mixing Zone:	10 m
Hydraulic Conductivity:	approx. 10.0E-03 cm/s
Local Flow Gradient:	0.0001

Material Parameters:

Coal Ash Runoff Rate:	13 cm/yr
Seepage through Fly Ash:	30 cm/yr
Downgradient Dilution Zone:	150 m
Dilution Zone Infiltration:	43 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	ODWO Reasonabl Use Conc. (mg/L)	Upgradient Groundwater Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Downgradient Infiltration Flow (cm3/s)	Upgradient Groundwater Flow (cm3/s)	Concentration at Property Line (mg/L)
TDS	3065	1474	1474	0.0004	0	0.02	0.0001	1505.0439
SO4	2007	917	917	0.0004	0	0.02	0.0001	938.2683
As	0.044	0.013	0.001	0.0004	0	0.02	0.0001	0.0018
Se	0.028	0.003	0.001	0.0004	0	0.02	0.0001	0.0015
B	28.6	1.43	0.237	0.0004	0	0.02	0.0001	0.7904
Cr	0.08	0.02	0.01	0.0004	0	0.02	0.0001	0.0114

Fly Ash Stabilized with: 10% Cement

TDS	N.A.	1474	1474	0.0004	0	0.02	0.0001	N.A.
SO4	430	917	917	0.0004	0	0.02	0.0001	907.4976
As	0.025	0.013	0.001	0.0004	0	0.02	0.0001	0.0015
Se	0.035	0.003	0.001	0.0004	0	0.02	0.0001	0.0017
B	0.8	1.43	0.237	0.0004	0	0.02	0.0001	0.2480
Cr	0.65	0.02	0.01	0.0004	0	0.02	0.0001	0.0225

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable.

TABLE XXV:

UHTOFF QUARRY CHEMICAL MASS BALANCE ANALYSIS - AQUATIC LIFE CRITERIA

Geometric Variables:

Fill Length: 400 m
Fill Width: 555 m
Fill Height: 9 m
Fill Volume: 2.0E+06 m3

Meteorological Data:

Rainfall: 92 cm/yr
Evapotranspiration: 38 cm/yr

Sump Characteristics:

Sump Flow: approx. 95000 cm3/s

Material Parameters:

Coal Ash Runoff Rate: 19 cm/yr
Seepage through Fly Ash: 35 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	PWQO (Aquatic Life) (mg/L)	Sump Water Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Required Sump Flow (cm3/s)
TDS	3065	N.A.	371	2461	1336	N.A.
SO4	2007	N.A.	92.3	2461	1336	N.A.
As	0.044	0.1	0.001	2461	1336	0
Se	0.028	0.1	0.001	2461	1336	0
B	28.6	N.A.	0.159	2461	1336	N.A.
Cr	0.08	0.1	0.01	2461	1336	0

Fly Ash Stabilized with 10% Cement

TDS	-	N.A.	371	2461	1336	N.A.
SO4	430	N.A.	92.3	2461	1336	N.A.
As	0.025	0.1	0.001	2461	1336	0
Se	0.035	0.1	0.001	2461	1336	0
B	0.8	N.A.	0.159	2461	1336	N.A.
Cr	0.65	0.1	0.01	2461	1336	23203.88

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable

TABLE XXVI:

UHTOFF QUARRY CHEMICAL MASS BALANCE ANALYSIS - DRINKING WATER OBJECTIVES

Geometric Variables:

Fill Length:	400 m
Fill Width:	555 m
Fill Height:	9 m
Fill Volume:	2.0E+06 m3

Meteorological Data:

Rainfall:	92 cm/yr
Evapotranspiration:	38 cm/yr

Sump Characteristics:

Sump Flow:	approx. 95000 cm3/s

Material Parameters:

Coal Ash Runoff Rate:	19 cm/yr
Seepage through Fly Ash:	35 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	DWO (mg/L)	Sump Water Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Required Sump Flow (cm3/s)
TDS	3065	500	371	2461	1336	75498.48
SO4	2007	500	92.3	2461	1336	14035.02
As	0.044	0.05	0.001	2461	1336	0
Se	0.028	0.01	0.001	2461	1336	7594
B	28.6	5	0.159	2461	1336	18510.47
Cr	0.08	0.05	0.01	2461	1336	2847.75

Fly Ash Stabilized with 10% Cement

TDS	N.A.	500	371	2461	1336	N.A.
SO4	430	500	92.3	2461	1336	0
As	0.025	0.05	0.001	2461	1336	0
Se	0.035	0.01	0.001	2461	1336	10547.22
B	0.8	5	0.159	2461	1336	0
Cr	0.65	0.05	0.01	2461	1336	56955

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable

TABLE XXVII:

UHTOFF QUARRY CHEMICAL MASS BALANCE ANALYSIS - IRRIGATION WATER CRITERIA

Geometric Variables:

Fill Length: 400 m
Fill Width: 555 m
Fill Height: 9 m
Fill Volume: 2.0E+06 m3

Meteorological Data:

Rainfall: 92 cm/yr
Evapotranspiration: 38 cm/yr

Sump Characteristics:

Sump Flow: approx. 95000 cm3/s

Material Parameters:

Coal Ash Runoff Rate: 19 cm/yr
Seepage through Fly Ash: 35 cm/yr

Unstabilized Fly Ash

Chemical Elements	*Leachate Conc. (mg/L)	PWQO (Irrigation Water) (mg/L)	Sump Water Conc. (mg/L)	Leachate Seepage Rate (cm3/s)	Leachate Runoff Rate (cm3/s)	Required Sump Flow (cm3/s)
TDS	3065	N.A.	371	2461	1336	N.A.
SO4	2007	N.A.	92.3	2461	1336	N.A.
As	0.044	0.1	0.001	2461	1336	0
Se	0.028	0.02	0.001	2461	1336	1598.736
B	28.6	0.75	0.159	2461	1336	178928.0
Cr	0.08	0.1	0.01	2461	1336	0

Fly Ash Stabilized with 10% Cement

TDS	N.A.	N.A.	371	2461	1336	N.A.
SO4	430	N.A.	92.3	2461	1336	N.A.
As	0.025	0.1	0.001	2461	1336	0
Se	0.035	0.02	0.001	2461	1336	2997.631
B	0.8	0.75	0.159	2461	1336	321.2351
Cr	0.65	0.1	0.01	2461	1336	23203.88

*Note: The leachate conc. for unstabilized fly ash comes from field investigations of disposal sites, whereas the leachate conc. for the stabilized fly ash comes from laboratory, static, leaching tests on pulverized samples. The results of these tests are not directly comparable, however for this report, a comparison was made. This is discussed in section 7.0 of this report.

N.A. - Not applicable

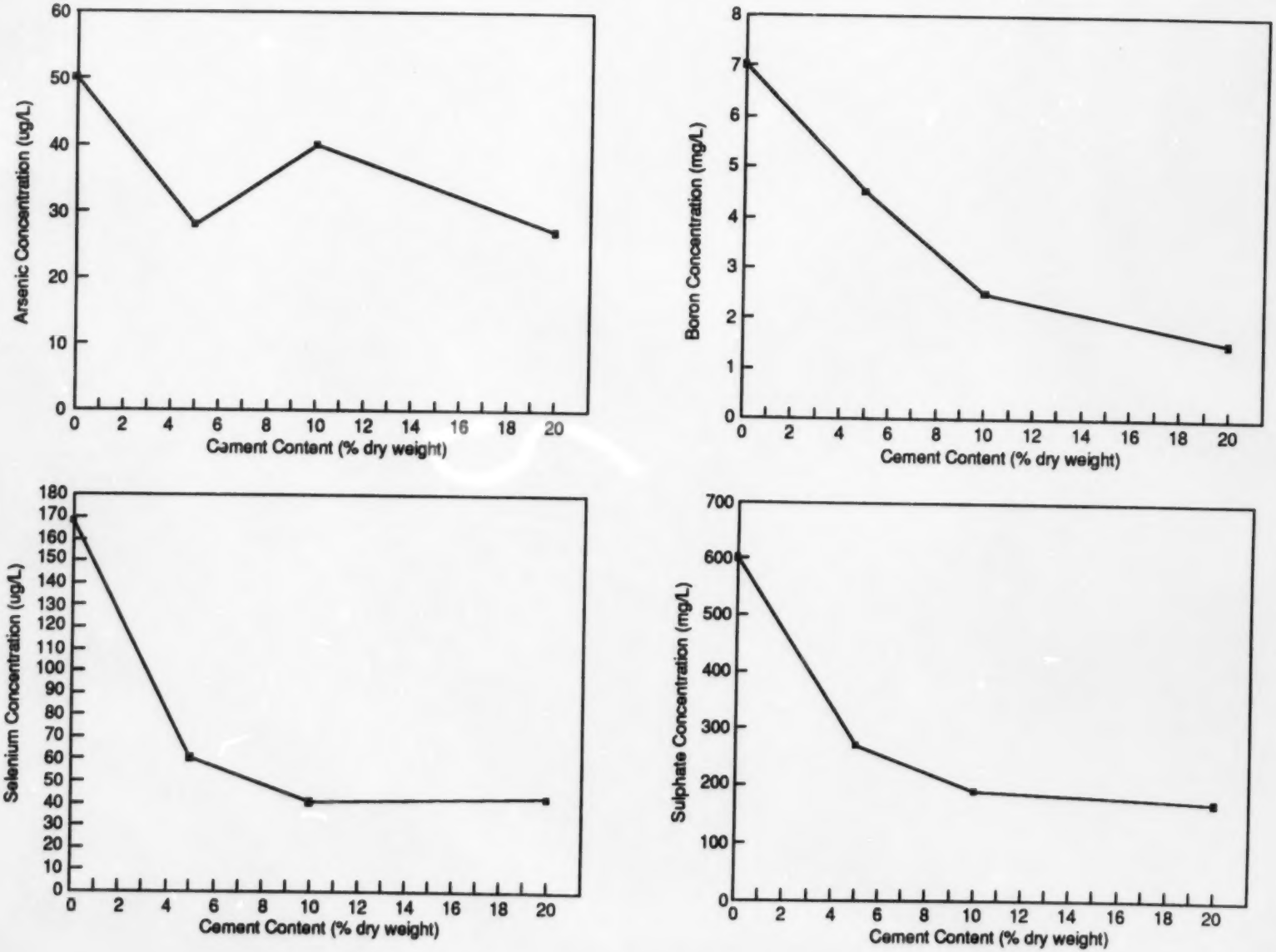
Arsenic Concentration (ug/L)
Cement Content (% dry weight)
Boron Concentration (mg/L)
Cement Content (% dry weight)
Selenium Concentration (ug/L)
Cement Content (% dry weight)
Sulphate Concentration (mg/L)
Cement Content (% dry weight)

FIGURE 1: EFFECT OF CEMENT ADDITION ON MAXIMUM CONTAMINANT CONCENTRATIONS OBSERVED IN STATIC LEACHING OF MONOLITH SAMPLES /7/.

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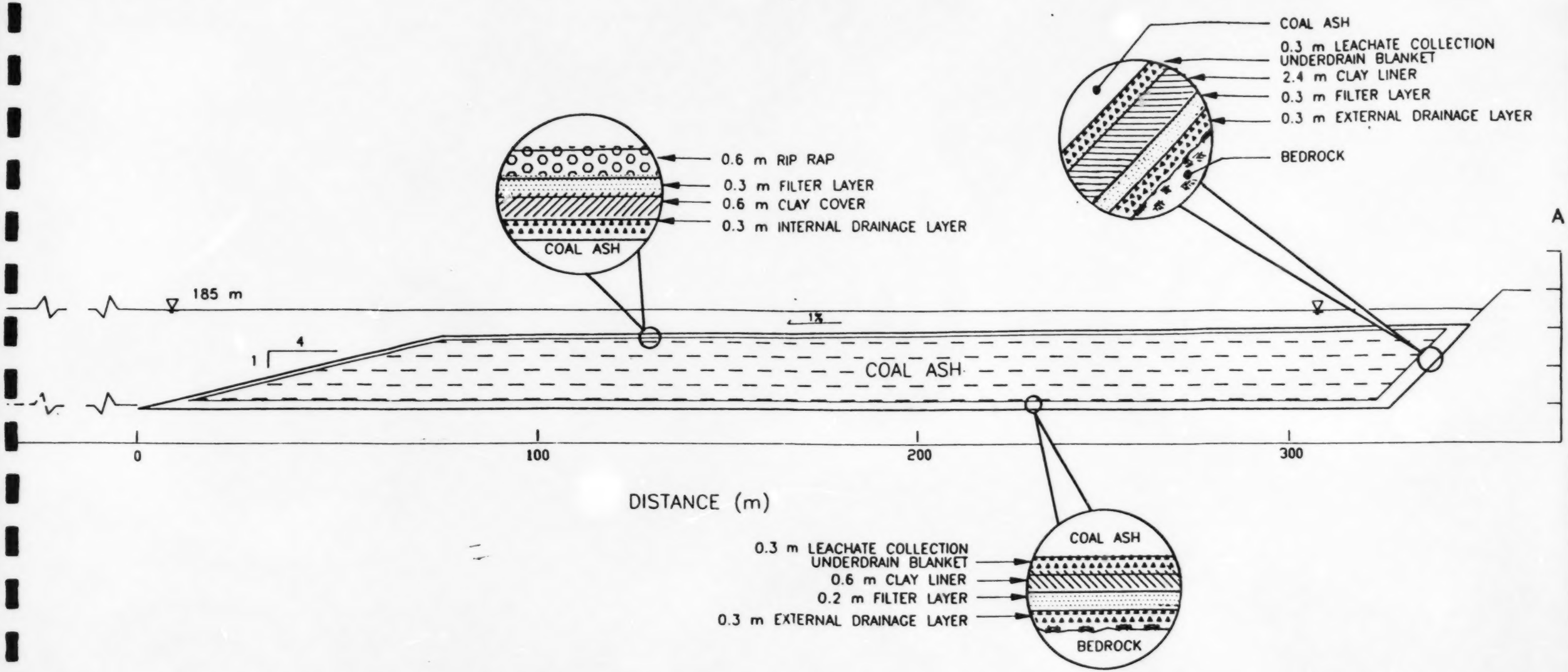
LINCOLN QUARRY - ORIGINAL DESIGN
CROSS-SECTION

FIGURE 2 /5/



SCALE 1 : 1,000

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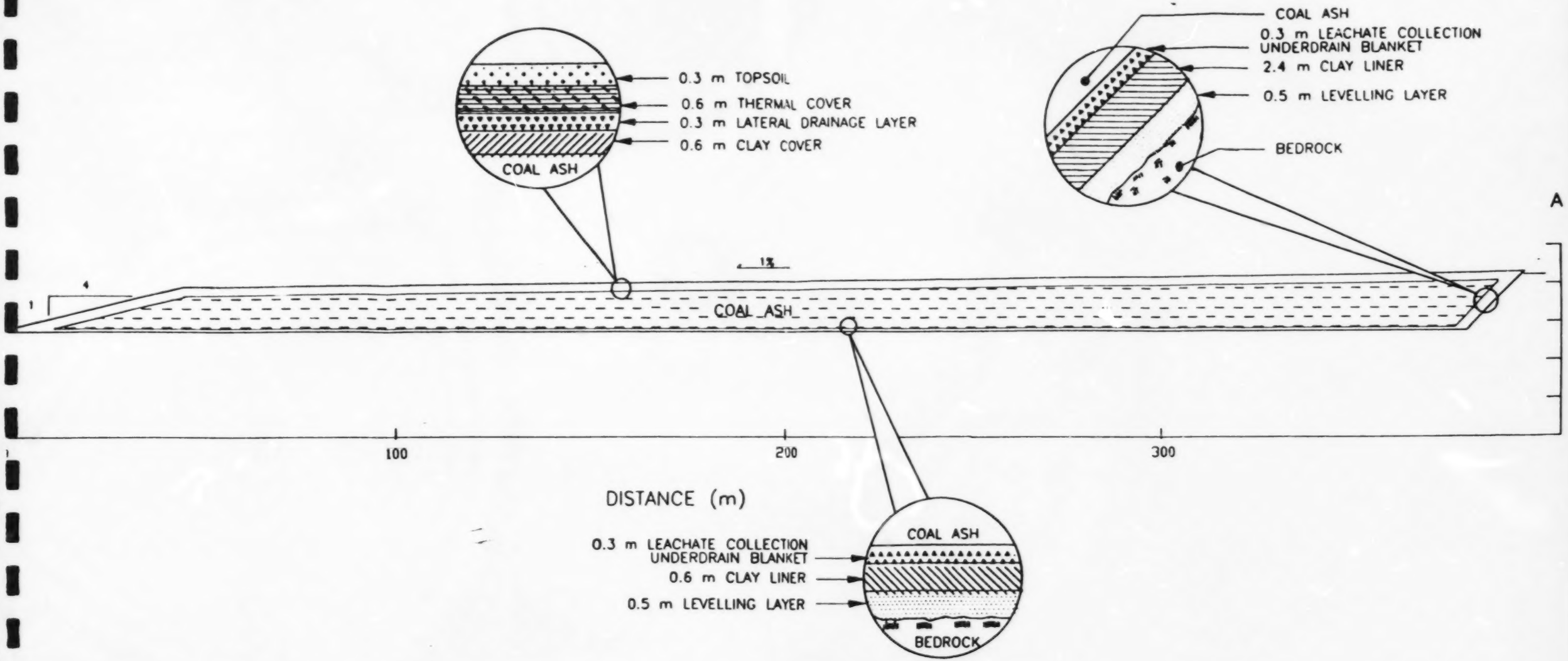
CAYUGA QUARRY – ORIGINAL DESIGN
CROSS-SECTION

FIGURE 3 /5/



SCALE 1 : 1,000

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FIGURE 4: LINCOLN QUARRY - STABILIZED FLY ASH WITH CLAY COVER/LINER, FILTER LAYER AND RIP RAP COVER

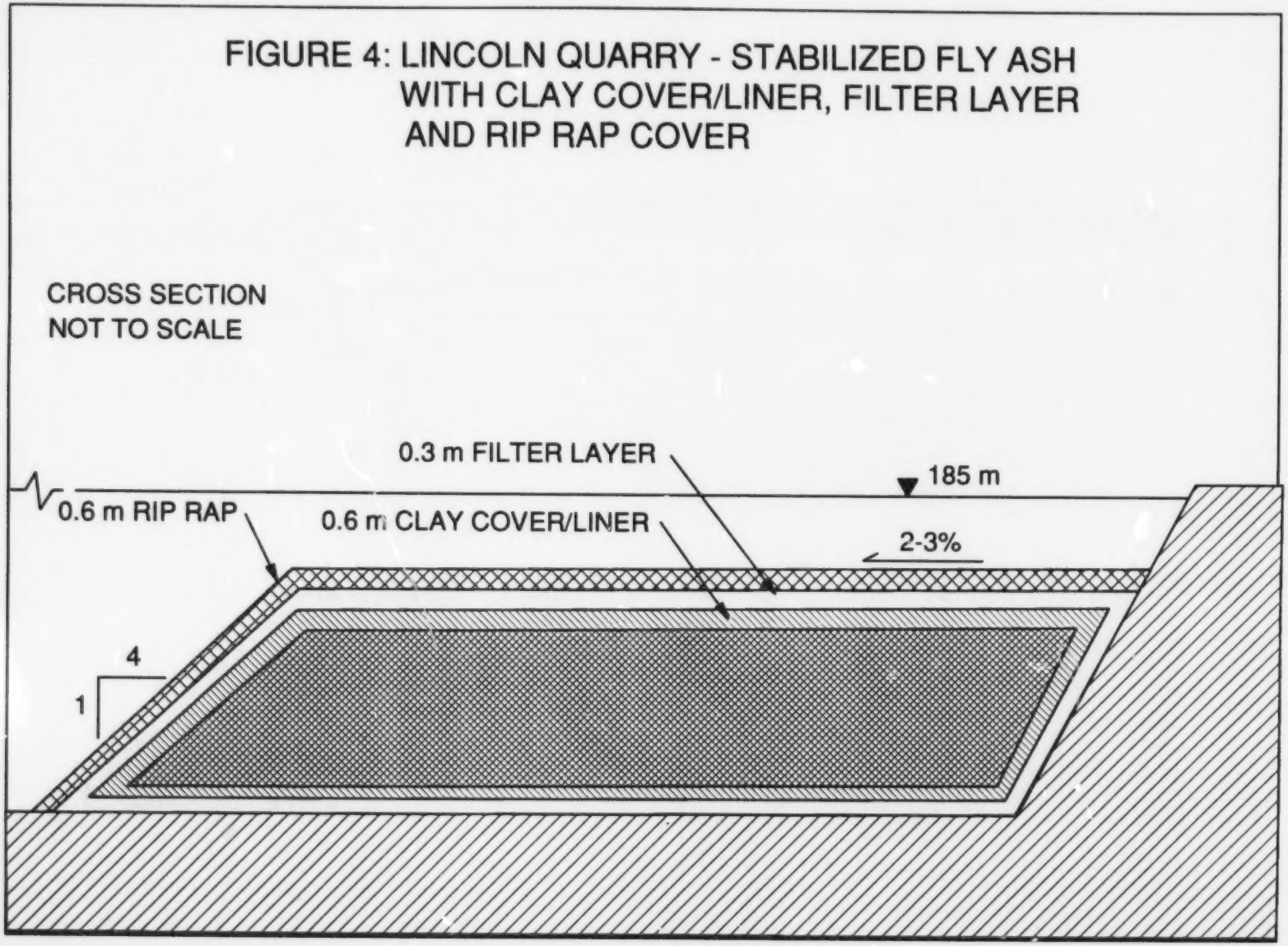


FIGURE 5: LINCOLN QUARRY - STABILIZED FLY ASH WITH FILTER LAYER AND RIP RAP COVER AND RIP RAP COVER

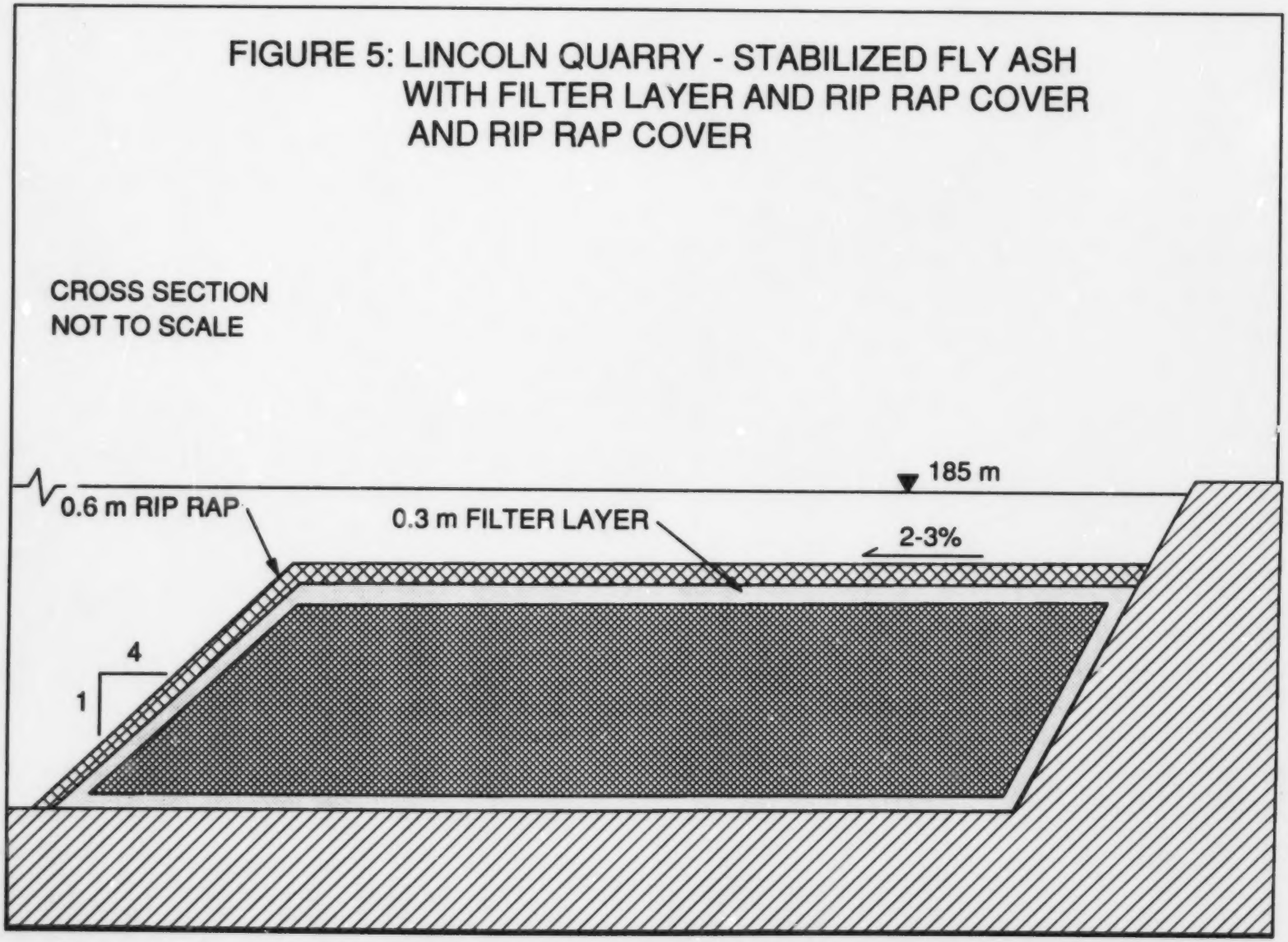
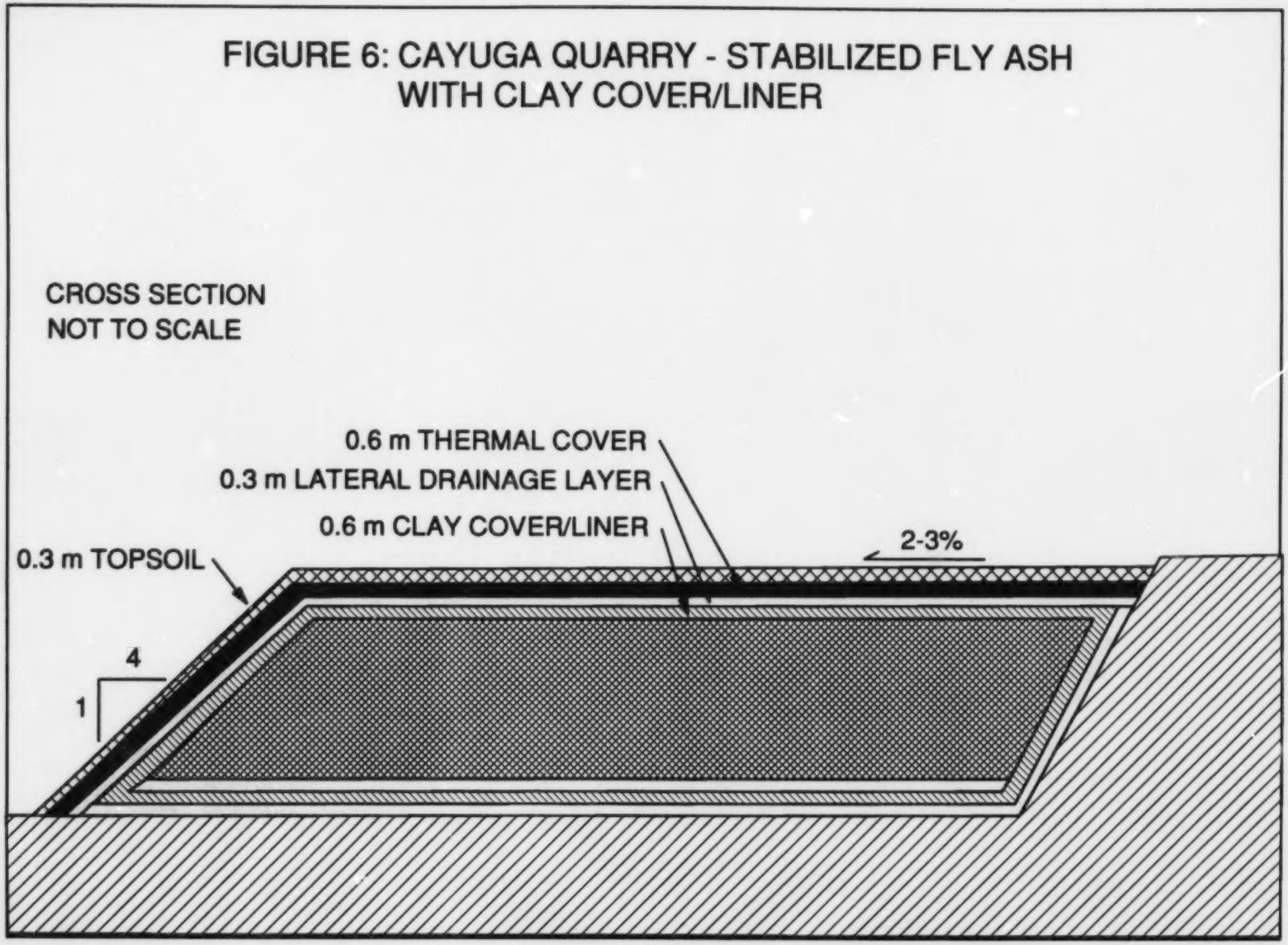


FIGURE 6: CAYUGA QUARRY - STABILIZED FLY ASH WITH CLAY COVER/LINER



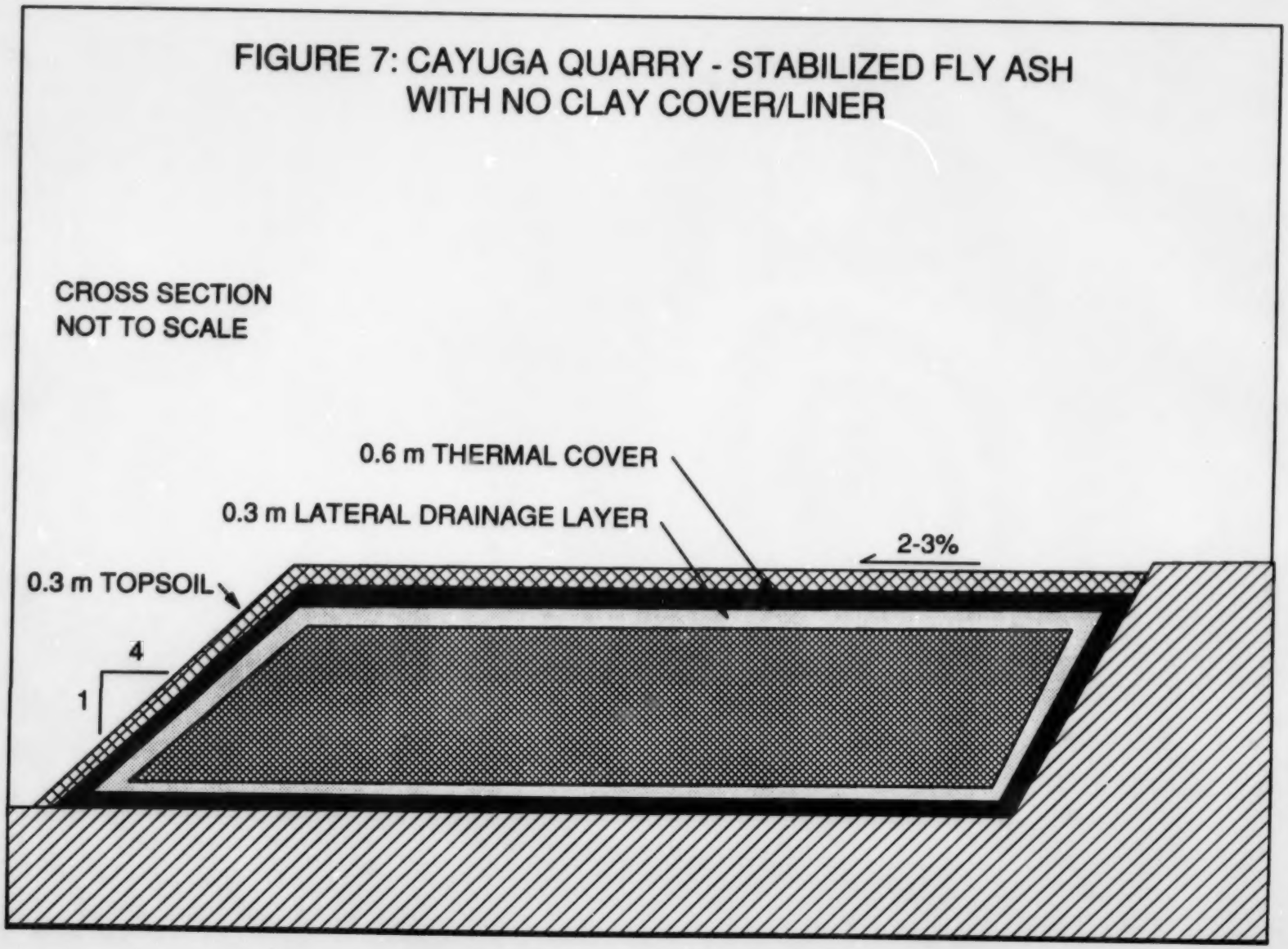
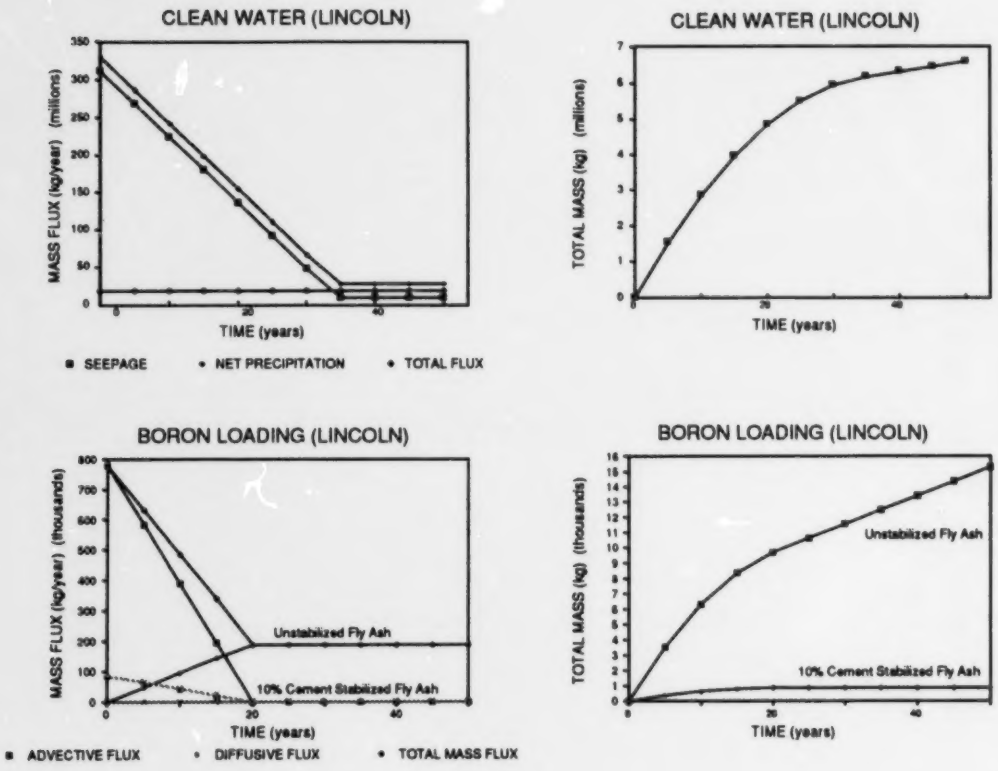
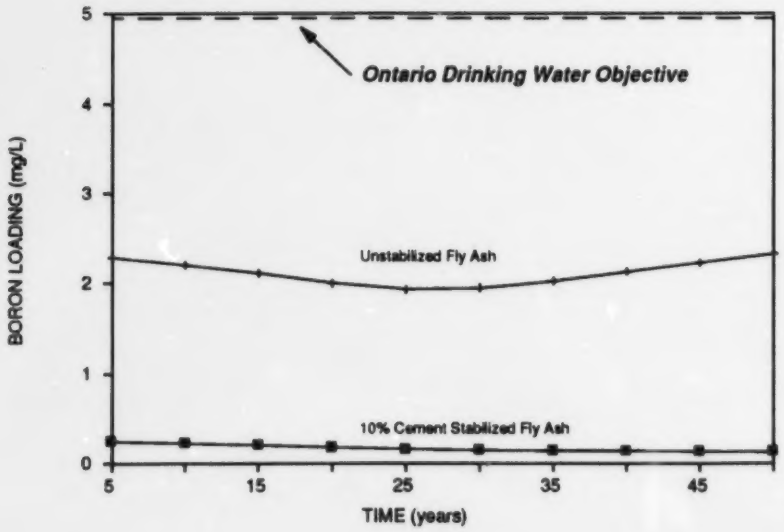


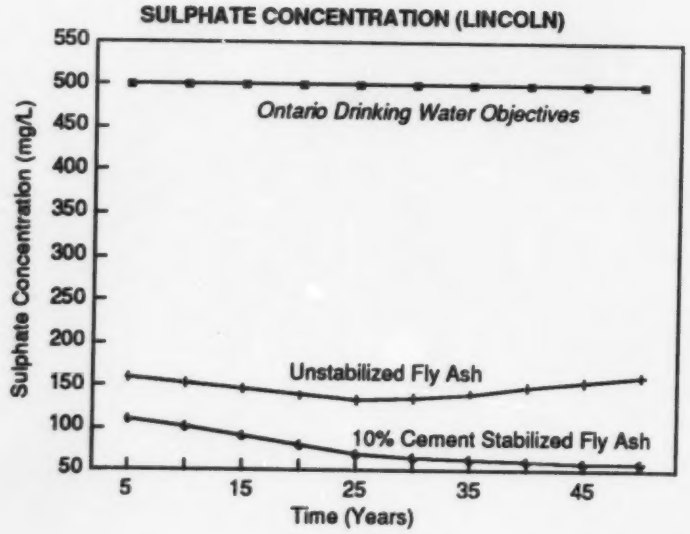
FIGURE 7: CAYUGA QUARRY - STABILIZED FLY ASH
WITH NO CLAY COVER/LINER
CROSS SECTION
NOT TO SCALE
0.6 m THERMAL COVER
0.3 m LATERAL DRAINAGE LAYER
2-3%
0.3 m TOPSOIL
4
1

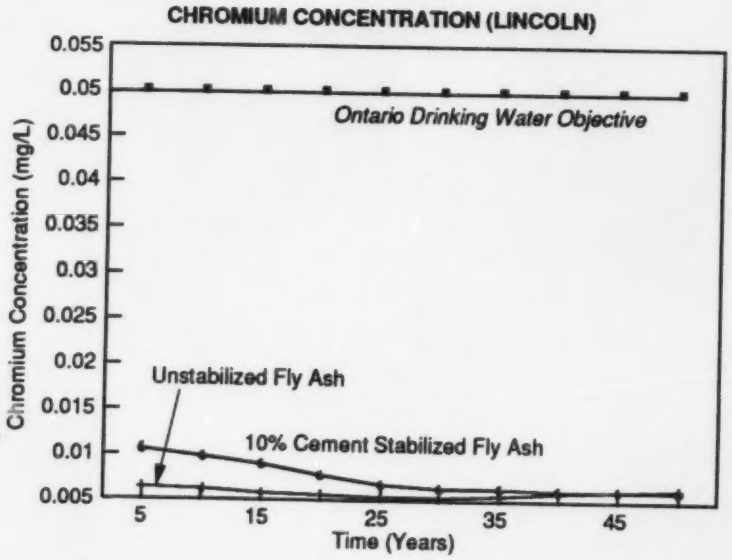
FIGURE 8: LINCOLN QUARRY - BORON LOADING

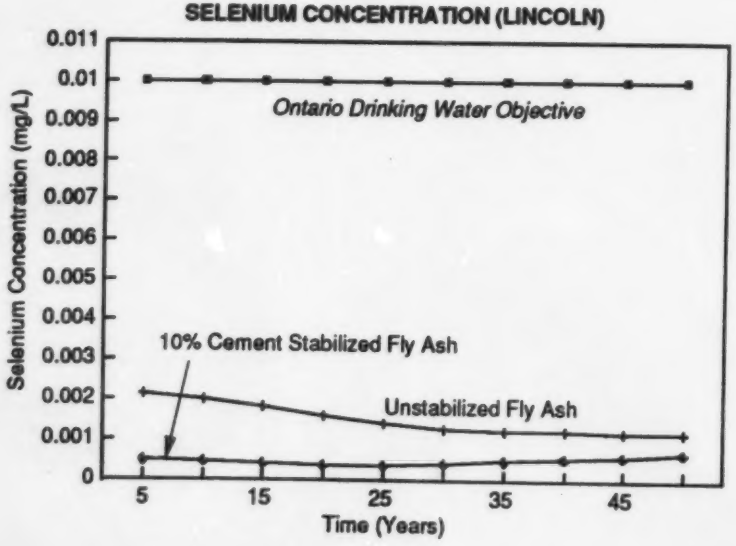


BORON CONCENTRATION (LINCOLN)









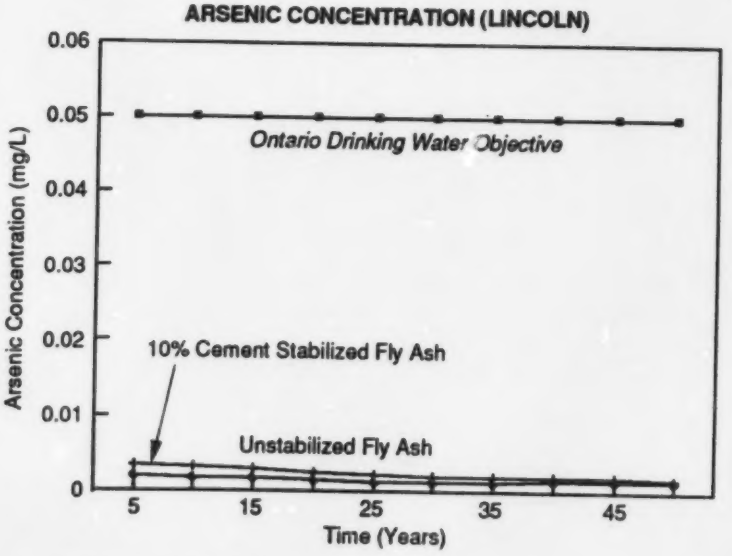
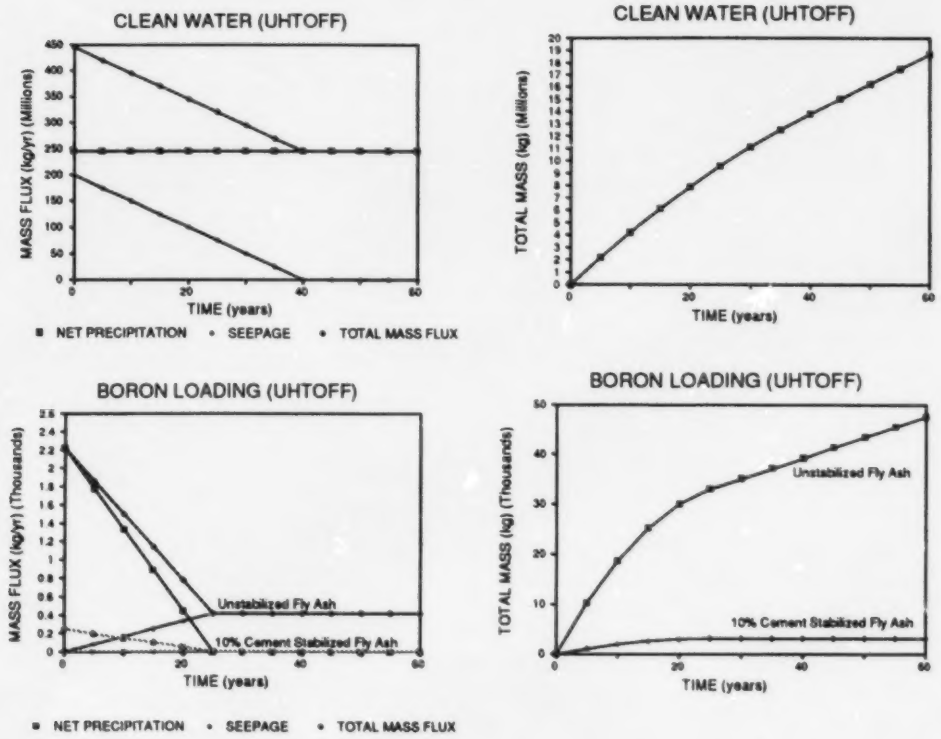
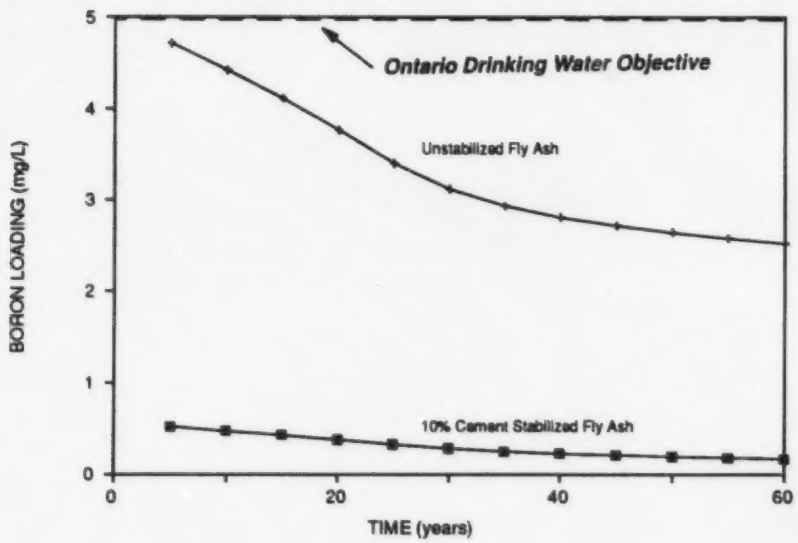


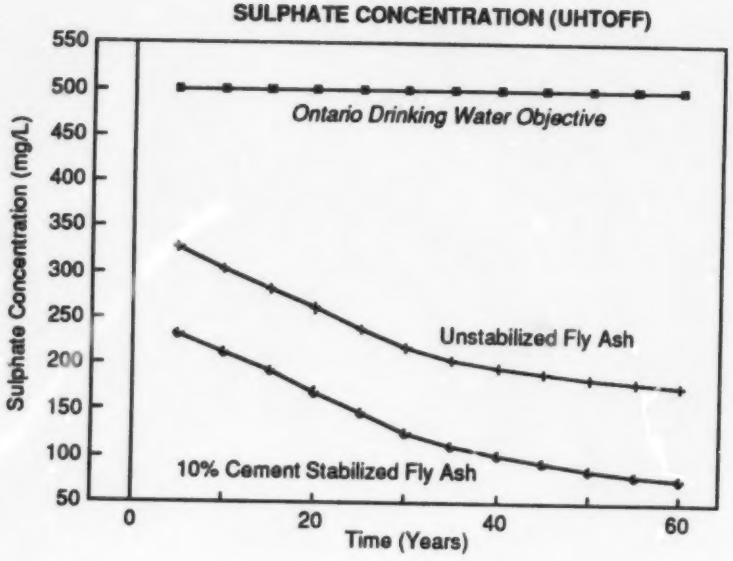
FIGURE 9: CONTAMINANT DIFFUSION AT LINCOLN QUARRY

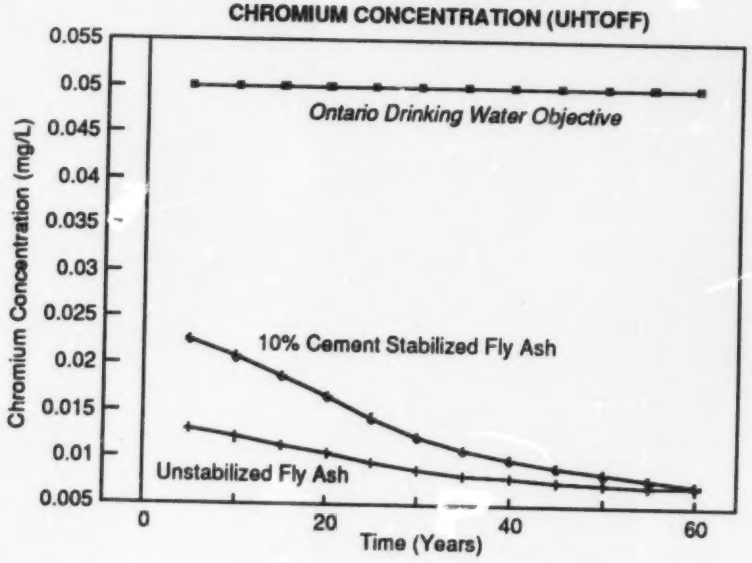
FIGURE 10: UHTOFF QUARRY - BORON LOADING

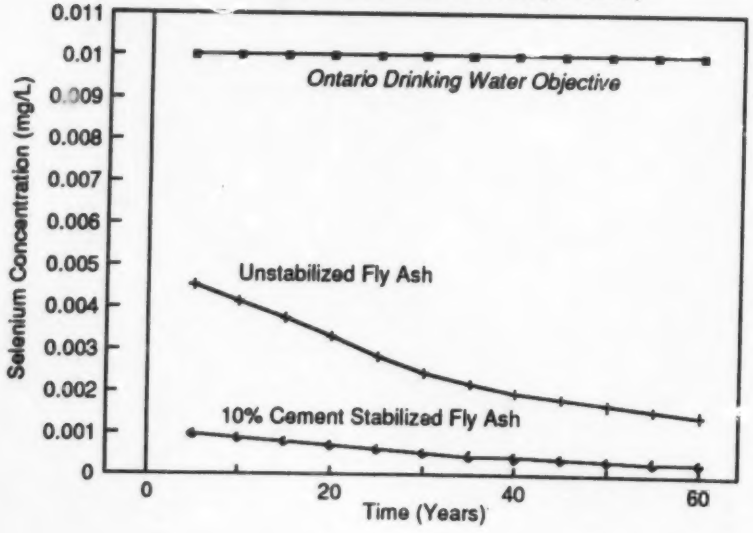


BORON CONCENTRATION (UHTOFF)









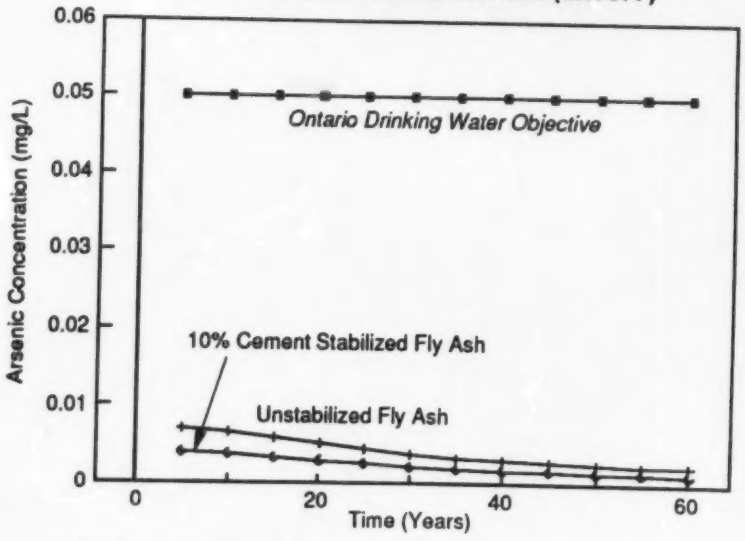
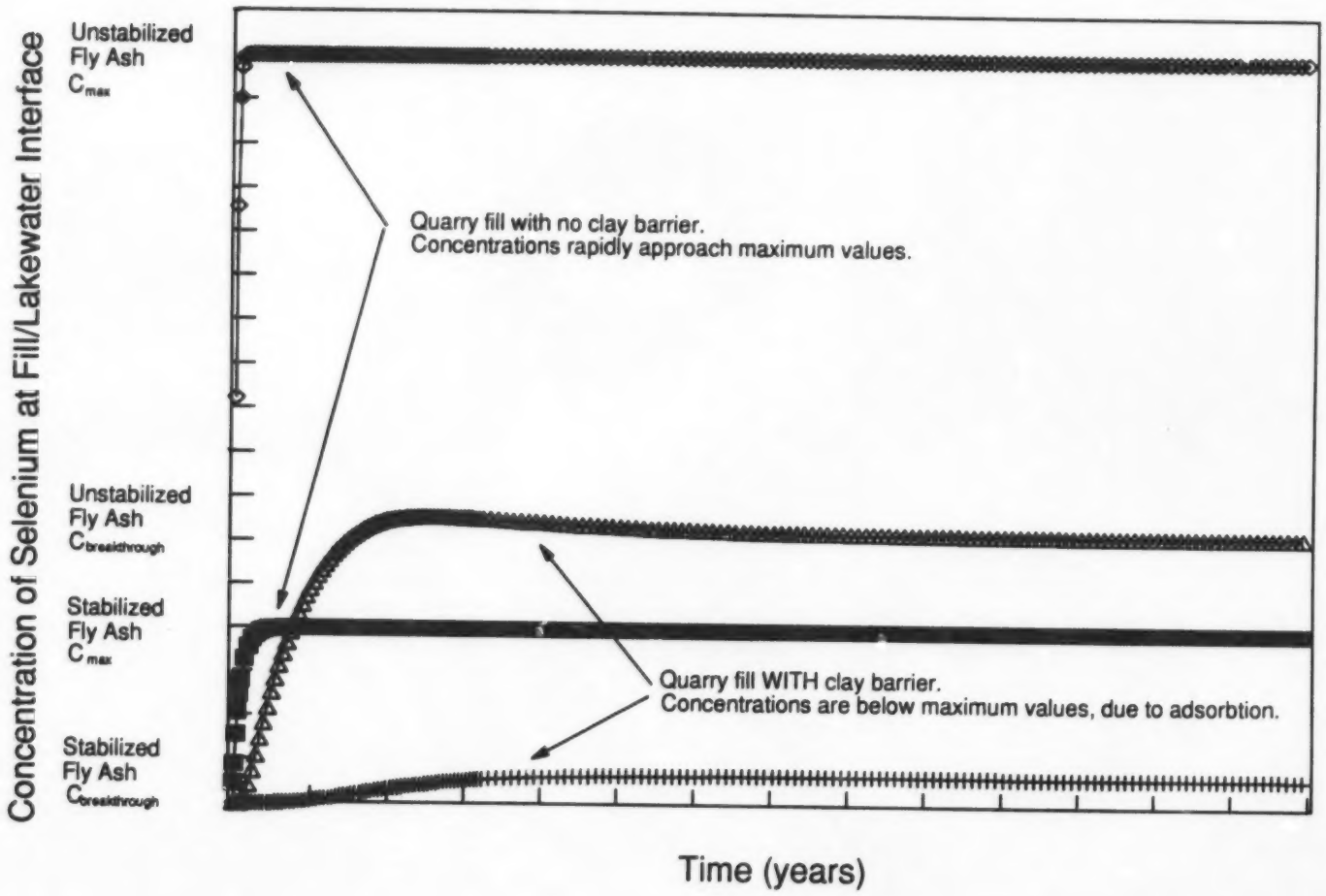


FIGURE 11: CONTAMINANT DIFFUSION AT UHTOFF QUARRY

1573-6-RD

FIGURE 12: RESULTS OF COMPUTER MODELLING


Concentration of Selenium at Fill/Lakewater Interface
Unstabilized Fly Ash C_{max}
Unstabilized Fly Ash $C_{breakthrough}$
Stabilized Fly Ash C_{max}
Stabilized Fly Ash $C_{breakthrough}$
Quarry fill with no clay barrier.
Concentrations rapidly approach maximum values.
Quarry fill WITH clay barrier.
Concentrations are below maximum values, due to adsorbtion.
Time (years)